MEG II 実験：2020年のコミッショニングの結果と今後の展望

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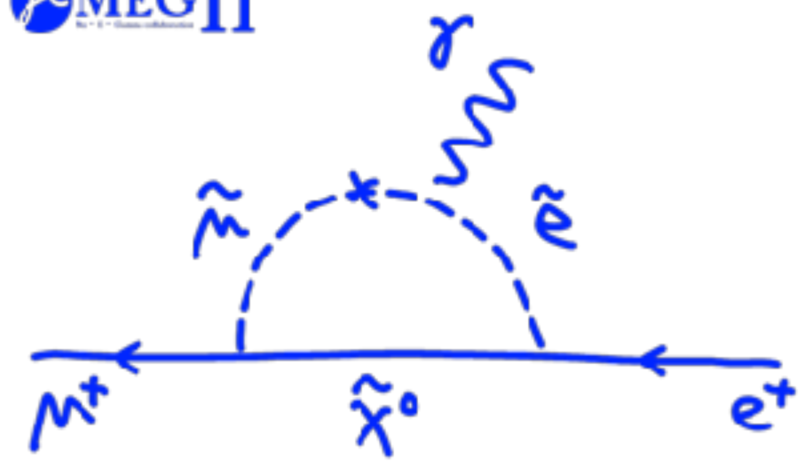
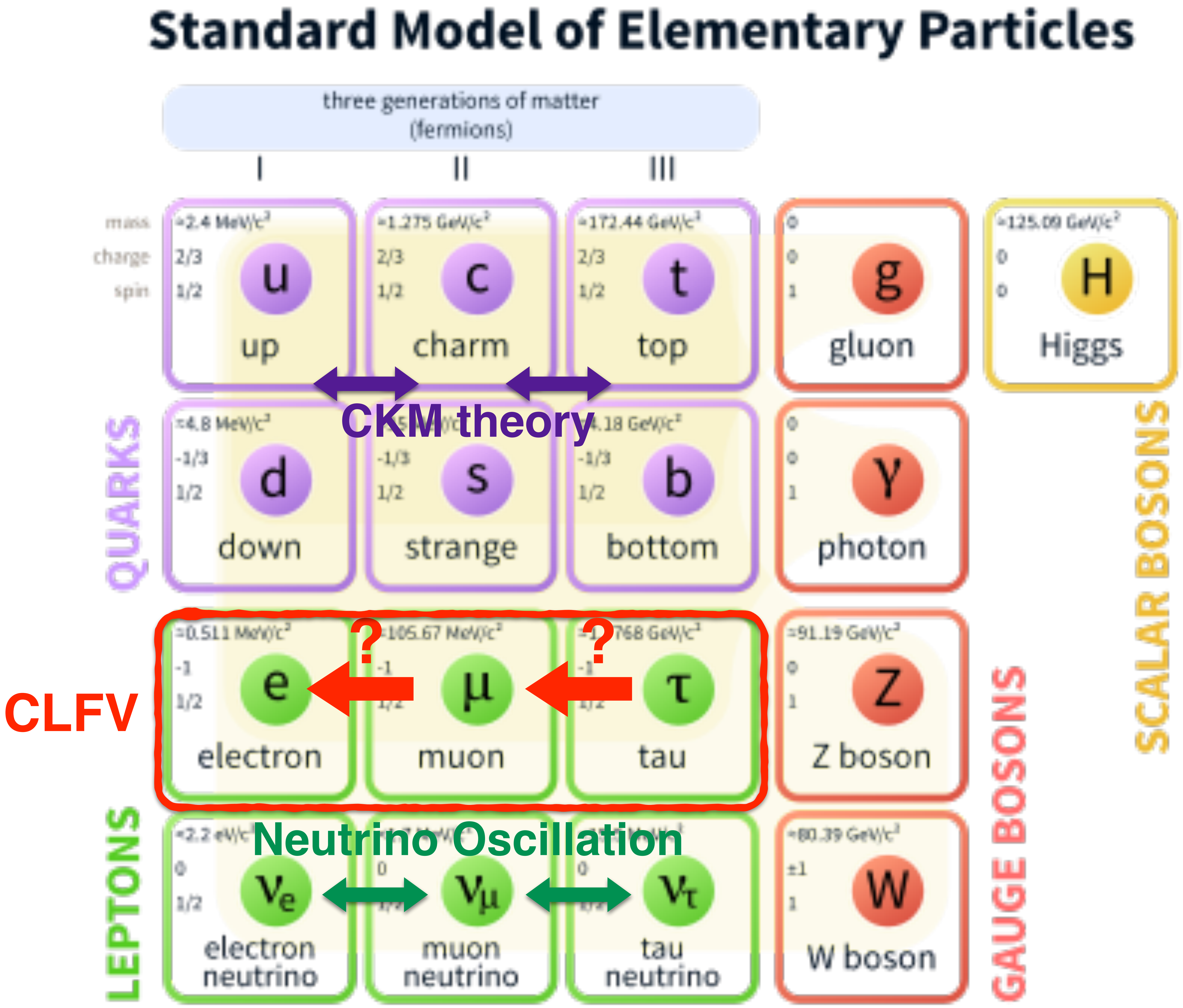


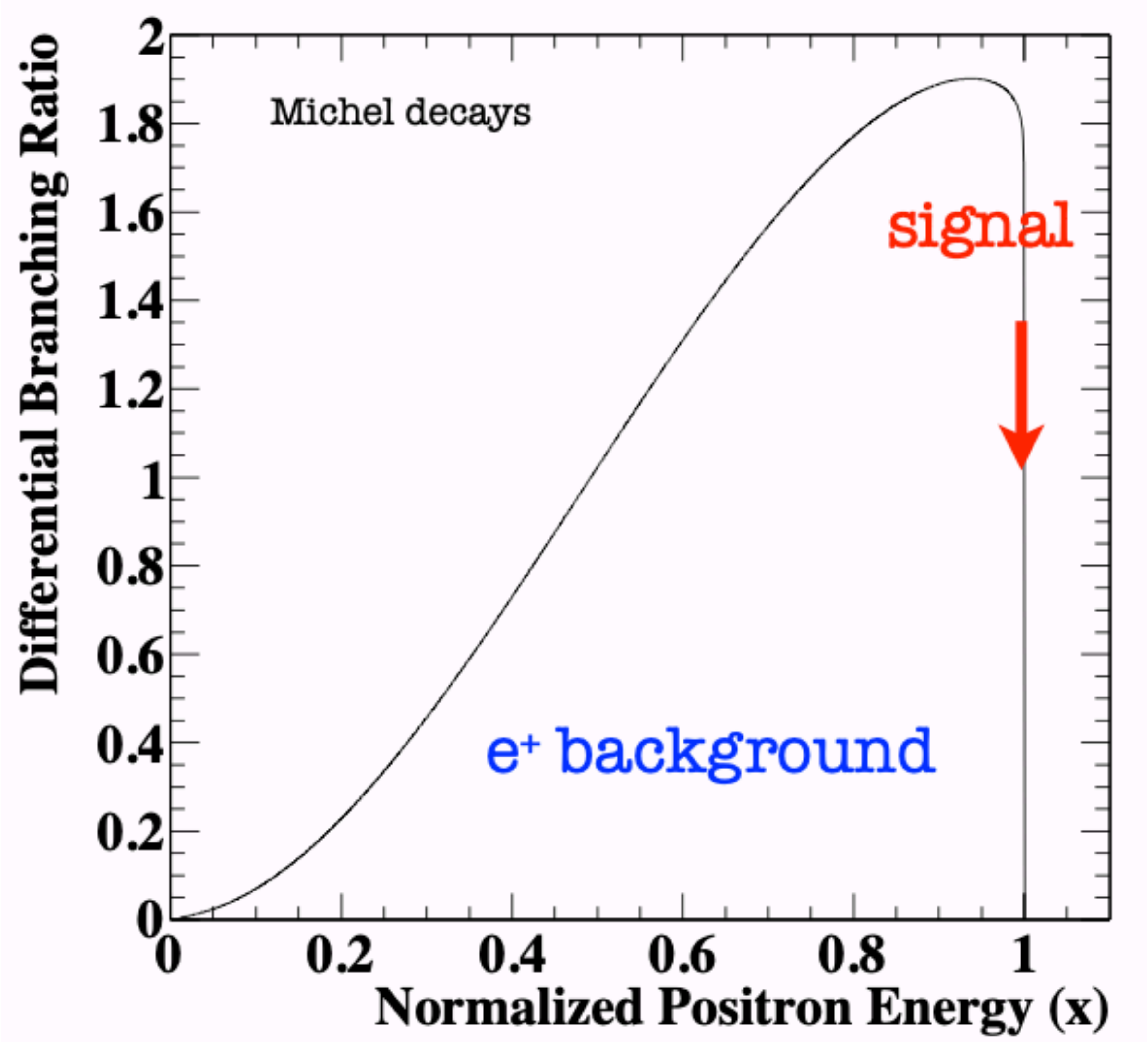
$\mu^+ \rightarrow e^+\gamma$ physics

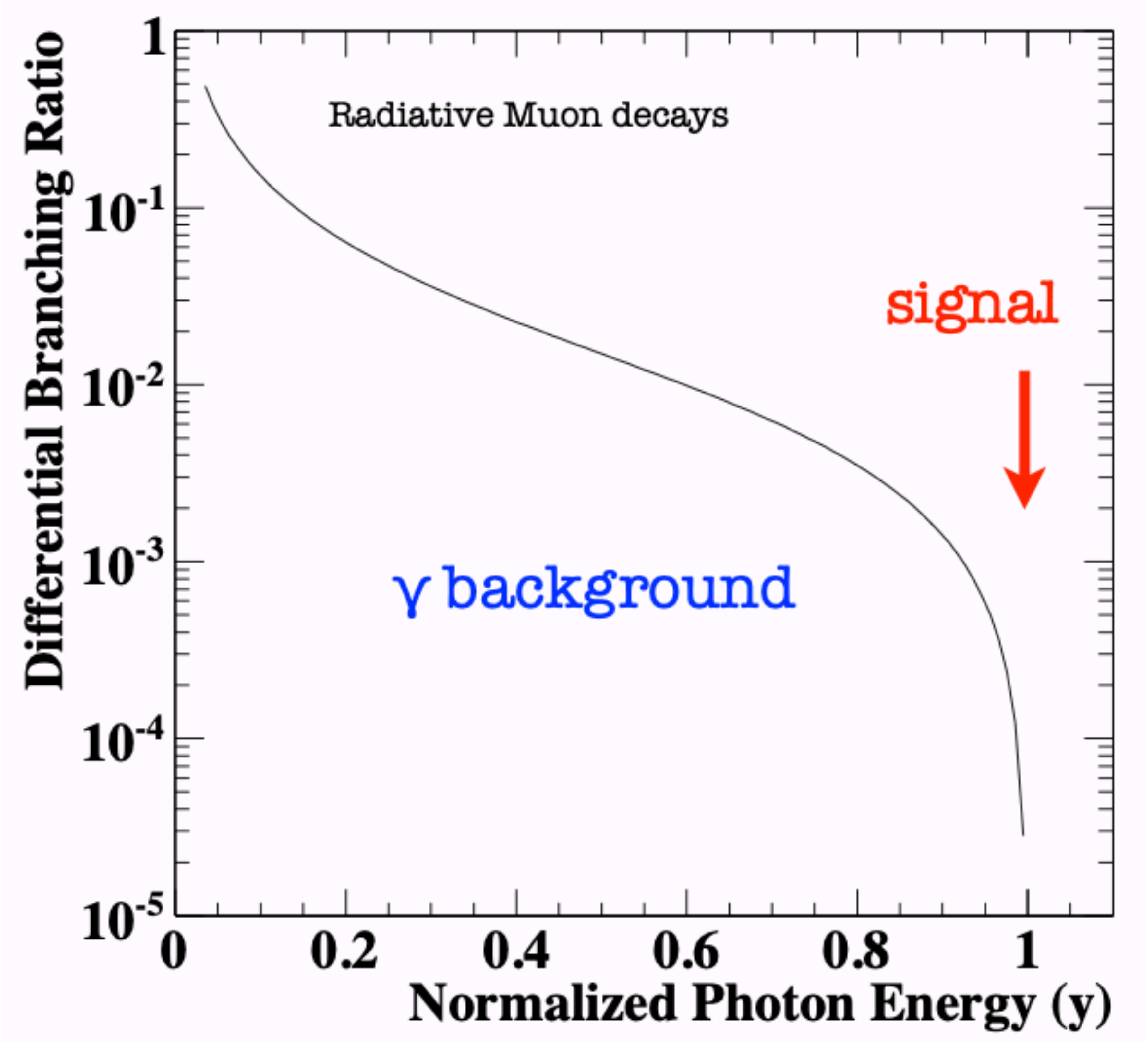
- Flavors (quarks, νs) are violated in SM
- Charged Lepton Flavor Violation
  - practically never occurs in SM : Br(μ→eγ) ~ 10^{-54}
- No reason to conserve flavors in new physics BSM
- CLFV is suitable to search for new physics
  - No background from SM, no theoretical uncertainty
- Many new physics predictions in a measurable region
  - SUSY-seesaw, SUSY-GUT etc.: Br(μ→eγ) ~ O(10^{-14})



$\mu^+ \to e^+\gamma$ event

- Signal
  - 52.8 MeV e^+, γ
  - back-to-back
  - Time coincidence
- Background
  - $\mu^+ \to e^+\nu\nu\gamma$
    - Radiative muon decay
  - Accidental
    - Dominant
- All the resolution improvements are crucial to keep the accidental background (N_{BG}) manageable

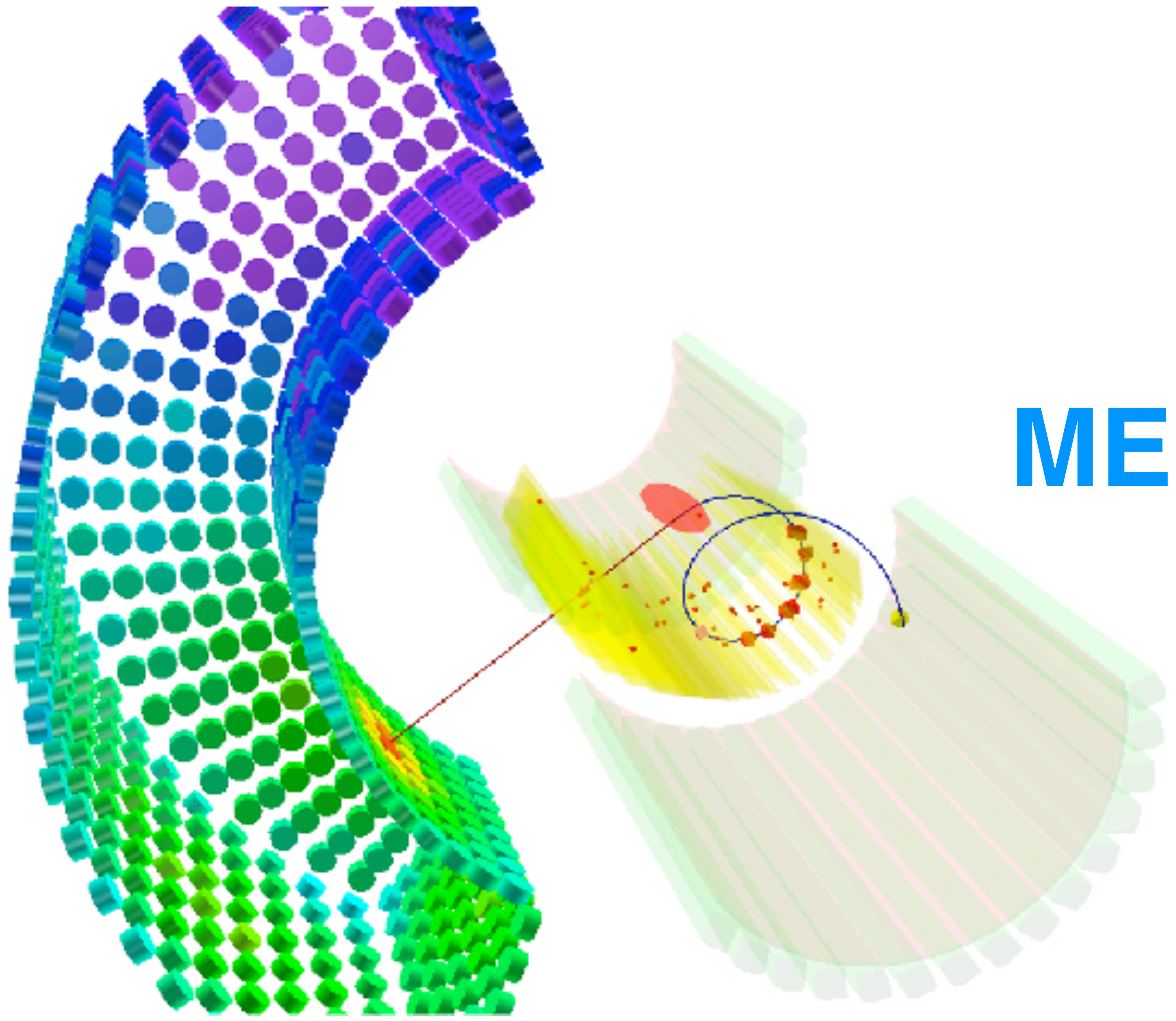


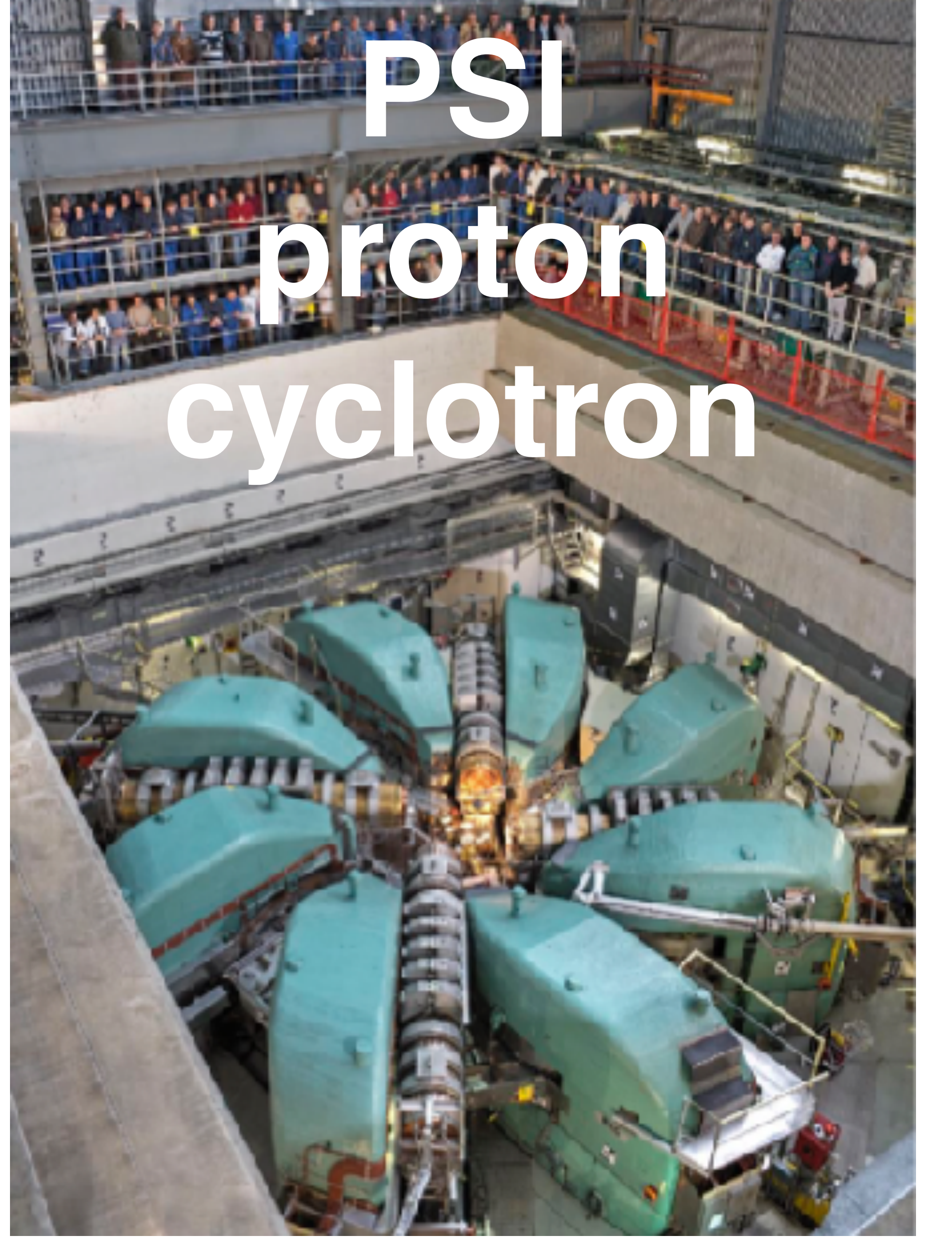


$$N_{BG} \propto R_\mu^2 \times \Delta E_\gamma^2 \times \Delta E_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$$

Beam rate (R_μ); Resolutions (ΔE_γ, ΔE_e, $\Delta\Theta_{e\gamma}$, $\Delta t_{e\gamma}$); Elapsed time (T)

MEG II experiment

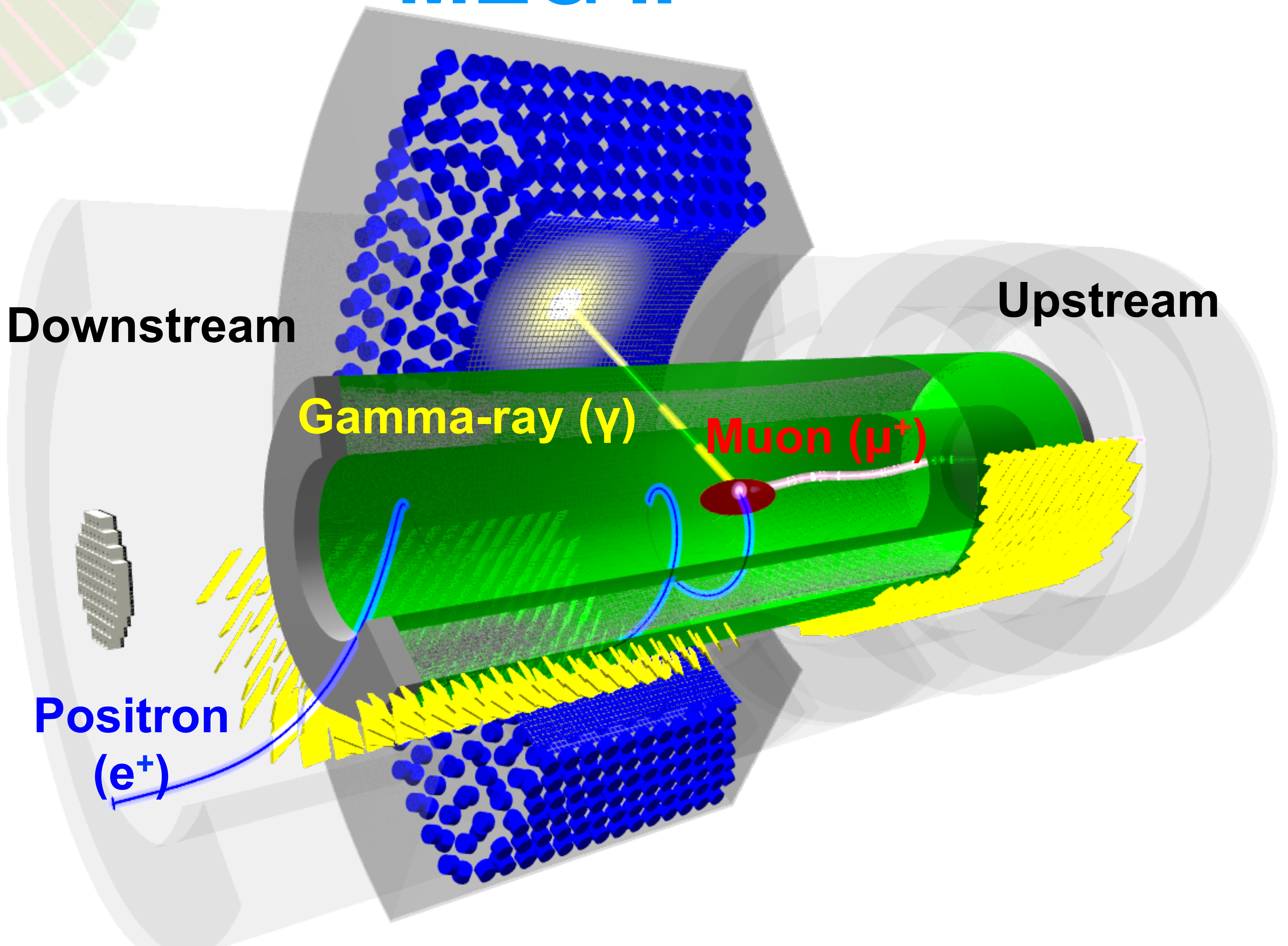




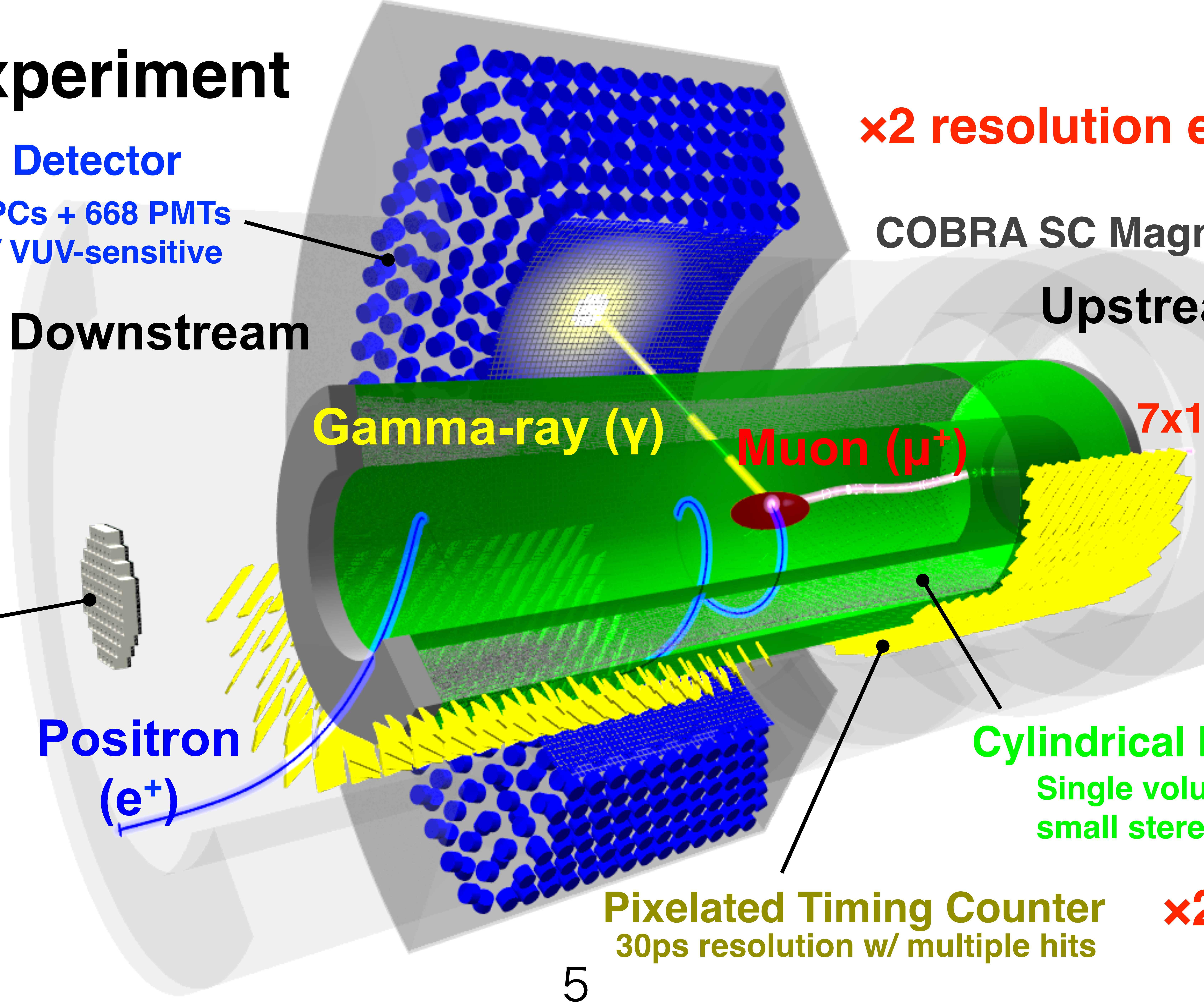
- MEG II experiment
  - Intensity frontier experiment
  - Upgrade from MEG experiment
  - To get clear evidence for BSM
- MEG final result (2016)
  - Br($\mu \to e\gamma$) < 4.2×10^{-13} @ 90%CL (5.3×10^{-13} Sensitivity)
- Twice intense muon beam
  - 7×10^{7} μ^{+}/s stopping at target
- Twice better resolutions for all detectors
- Twice better detection efficiency
- Search for Br($\mu \to e\gamma$) ~ 6×10^{-14} (90% CL sensitivity) in 3 year physics run

MEG

MEG II

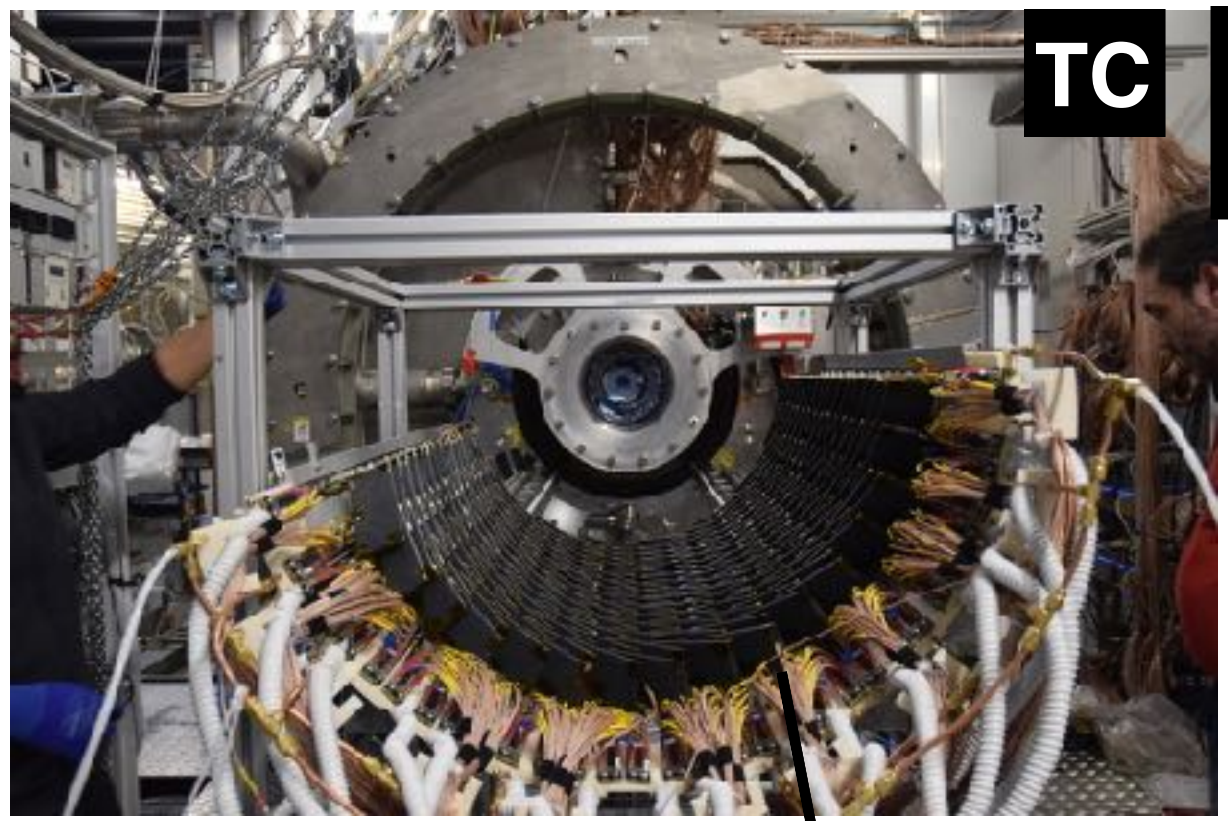


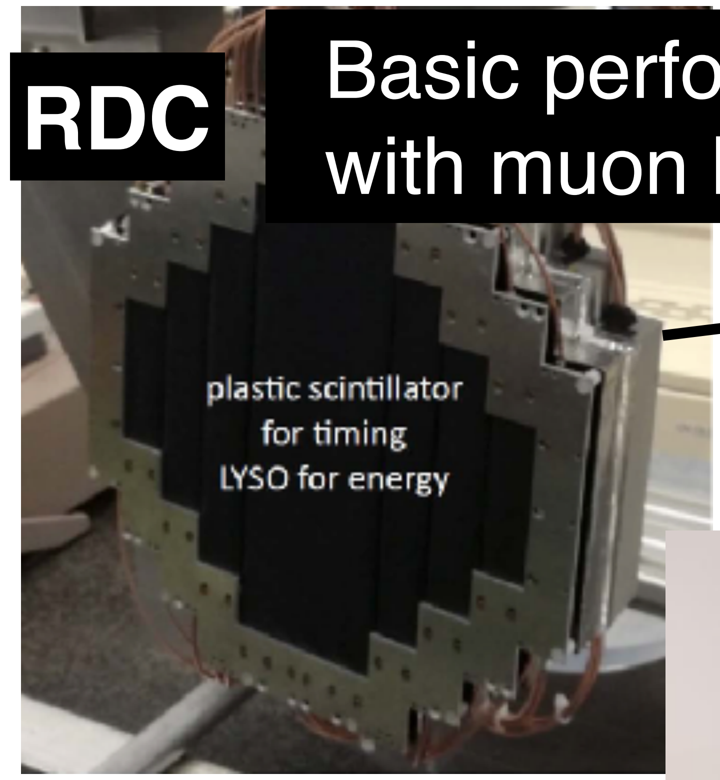
MEG II Experiment

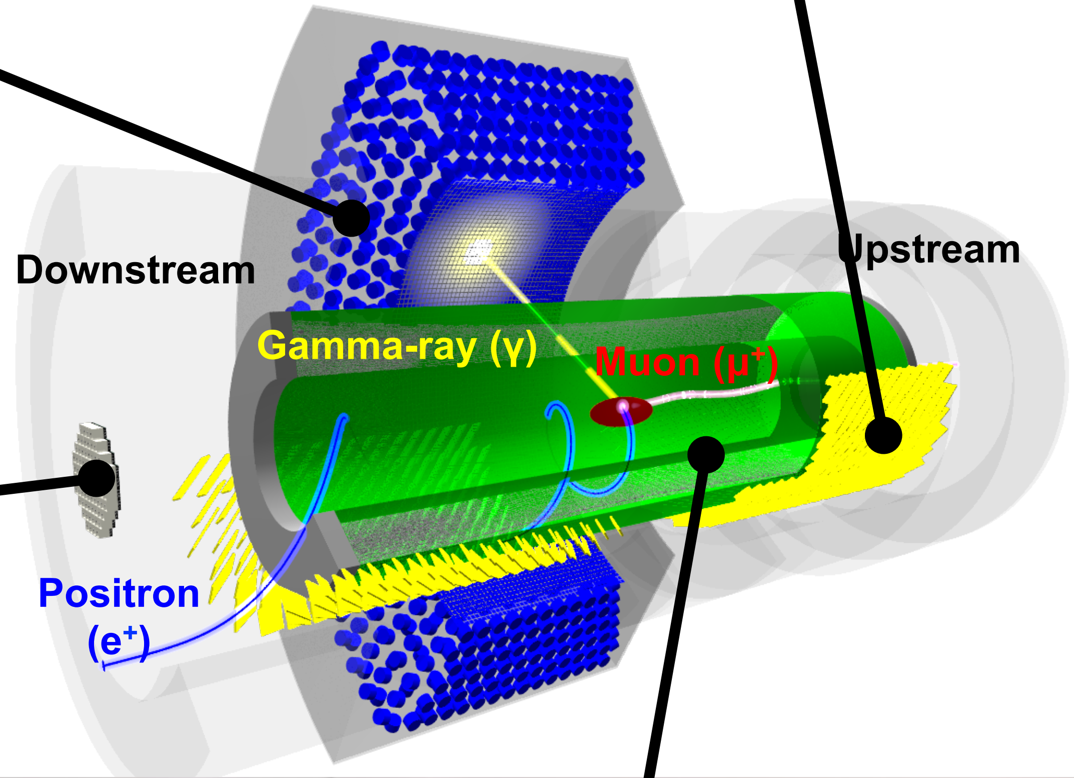


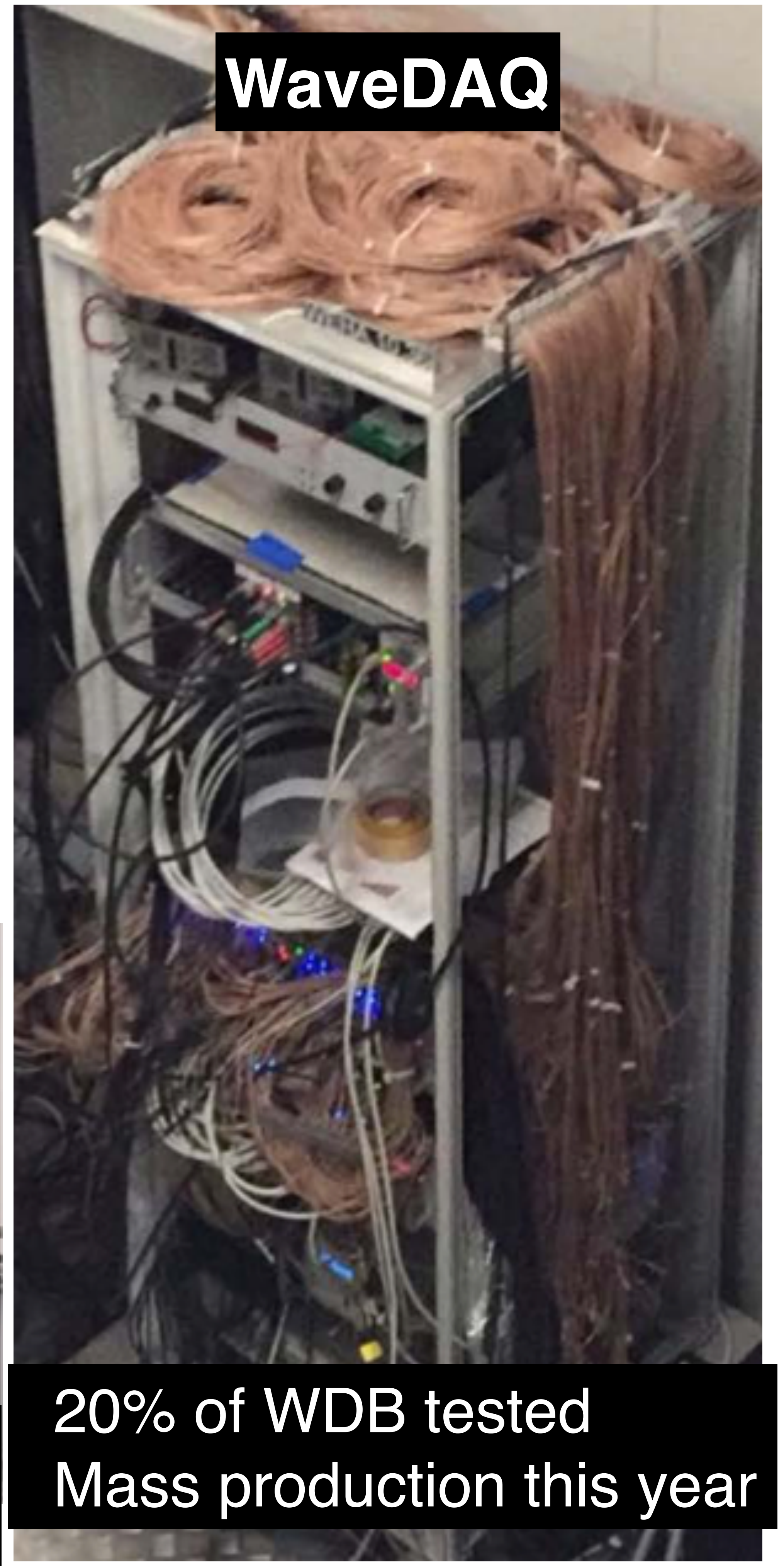
MEG II Status before 2020 run

- All detectors are constructed
- 20% of electronics readout channels are produced and tested







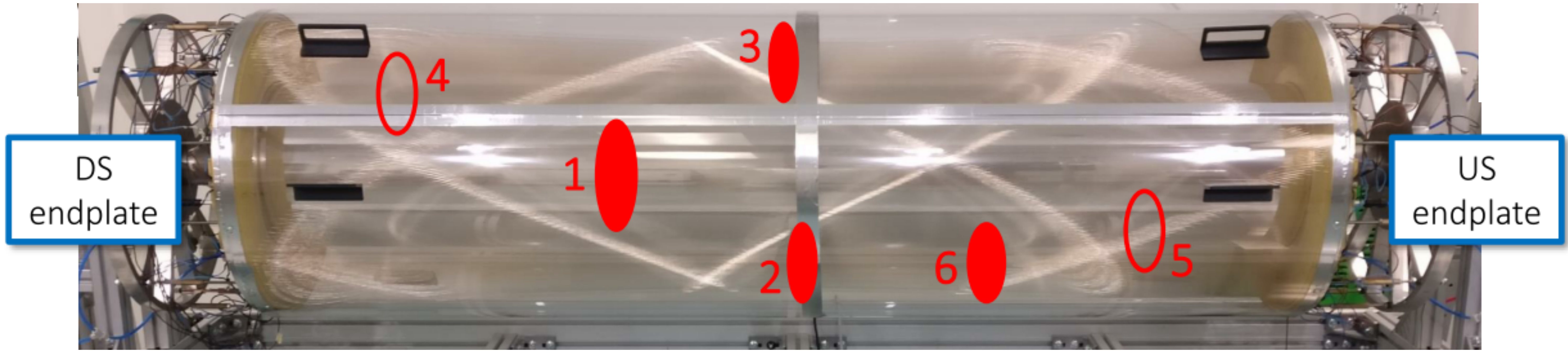


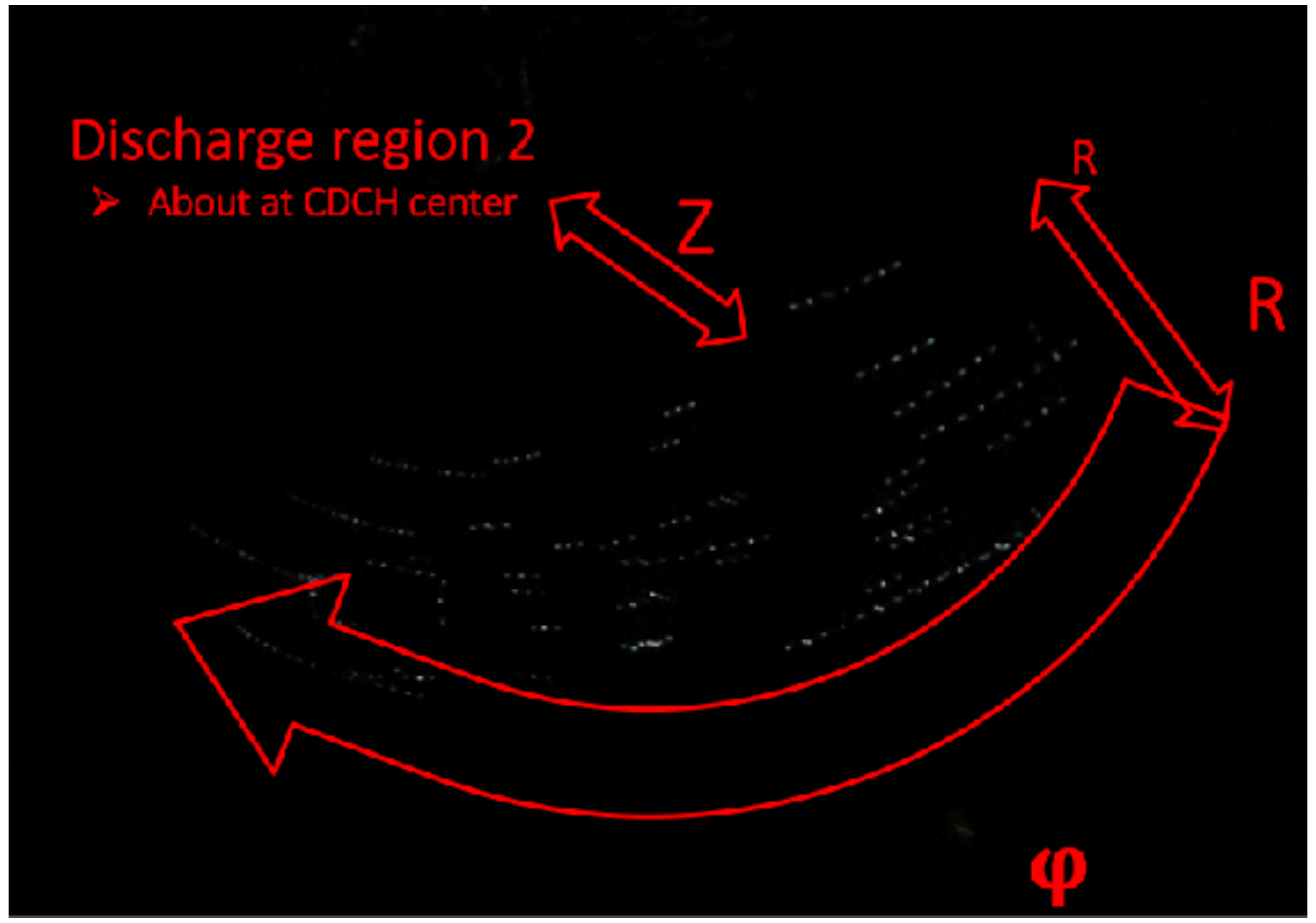
2020 run and issues

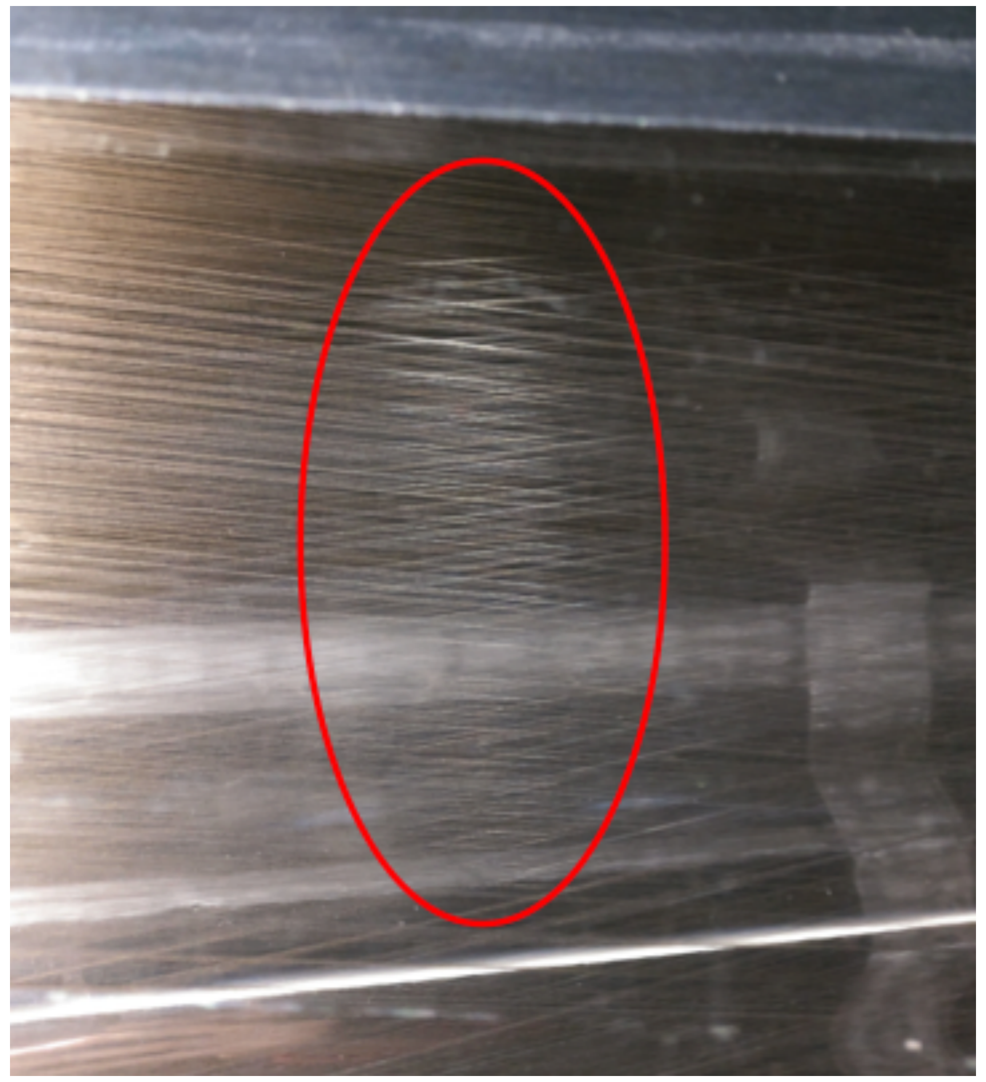
- Despite COVID, necessary maintenance work was restarted at PSI from July 2020
- All detectors were assembled again in Sep.
- Successful beam time in Oct. - Dec.
  - Muon beam for detector commissioning in Oct. and Dec.
  - Special run with Charge EXchange (CEX) reaction in Nov.
  - Beam test for US RDC prototype at the end
- Issues
  - Drift chamber
    - High current under muon beam, wire breaking
  - Liquid xenon detector
    - Performance check at 55 MeV
    - Large degradation of MPPC & PMT in beam

Drift chamber discharge problem

- High current was an issue in run 2019
- Drift chamber discharges observed by eye in 2020 spring
  - Absolute dark environment
  - point-like lights like “corona discharges”
  - Whitish deposits seems to be formed
  - High currents observed at 1200V w/o additives (Working point ~1500V)
- Solutions
  - additives for helium-isobutane gas are suggested by papers
    - CO_2, Oxygen, water, alcohols, etc.
  - Babar NIM A515(2003)
  - LHCb JINST 14 (2019) P11031

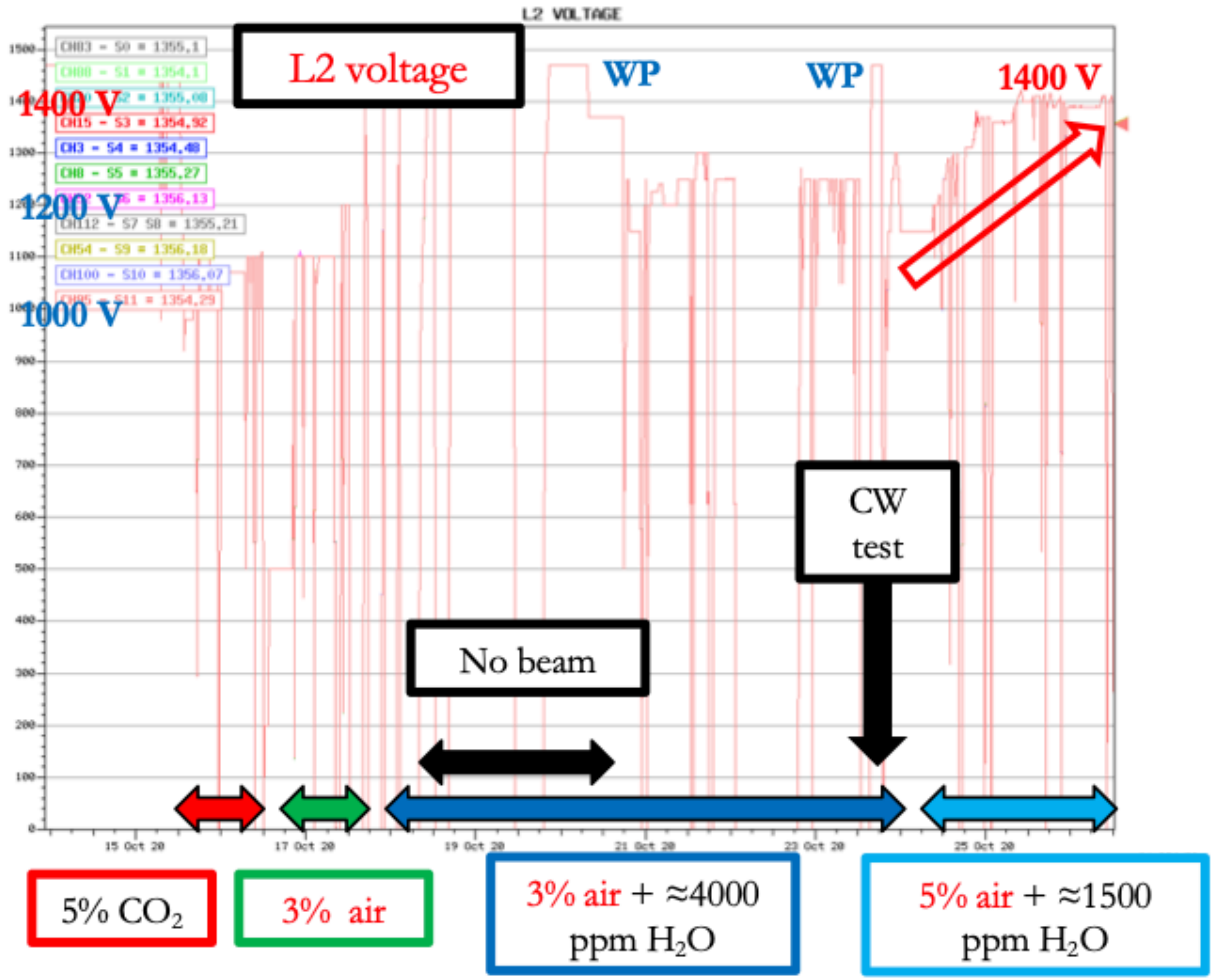






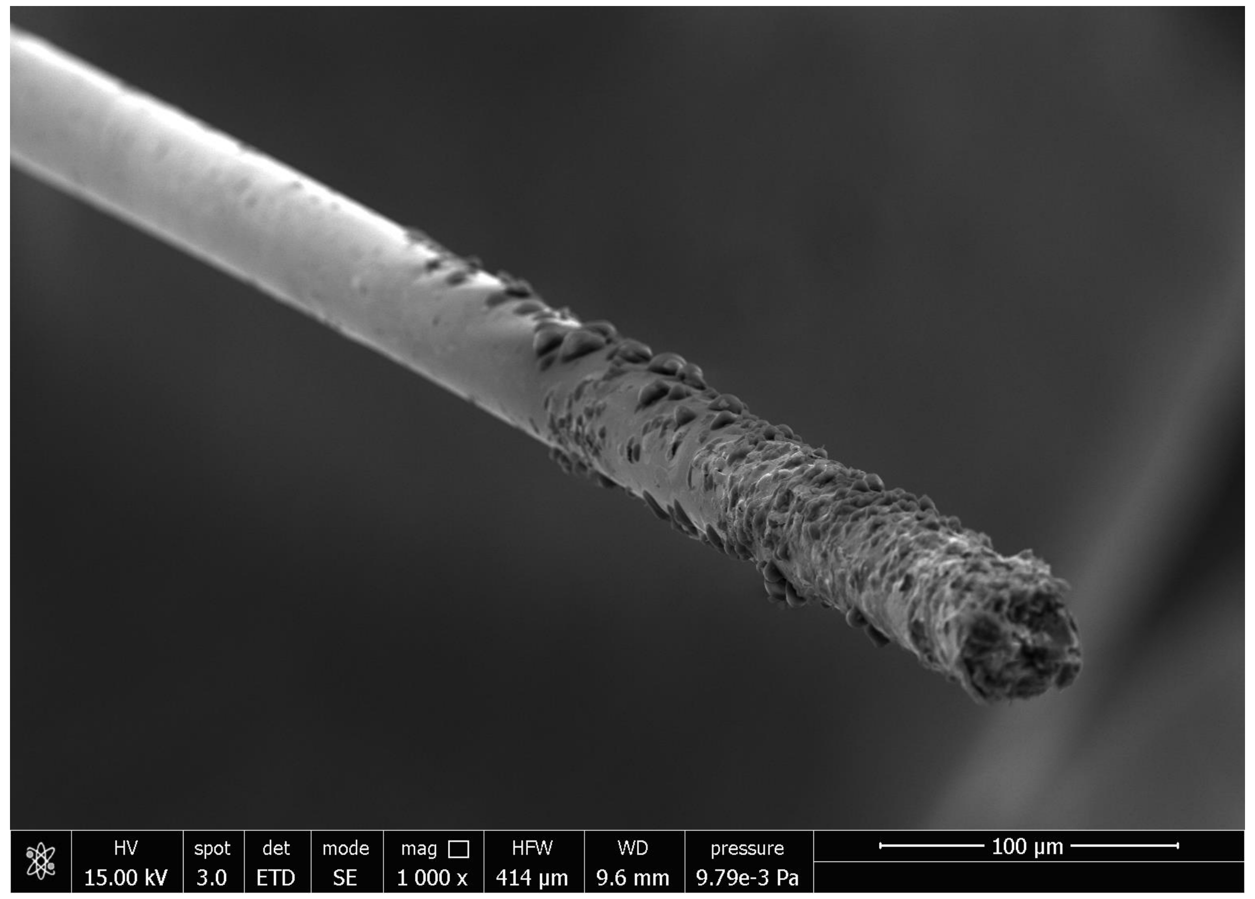
Solution for drift chamber discharge

- Different gas mixtures were tested under muon beam run in 2020
  - Only water, CO_2, or O_2 was not effective
- Adequate gas mixture was finally found
  - He:iso-butane= 90:10 +H_2O 3500ppm+pure O_2 2%
  - Nominal HV at MEG II intensity ($7\times10^7\mu$/s) was achieved.
- One wire might be broken during this test
  - Due to corrosion by water?
  - Water was replaced with 1% Isopropyl alcohol, and it worked!
- O_2 concentration reduced down to 0.5%
  - Attachment of electrons loses electron in the drift (lower gain)
- Final gas mixture
  - He:iso-butane = 90:10 + Isopropanol 1% + O_2 0.5%



Drift chamber broken wire problem

- Wire breaking was induced by humidity
  - Corrosion evolved with water & wire tension
- Drift chamber had been operated in closed condition with dry environment
  - Small amount of water vapor (13% relative humidity) induced a wire breaking in 2020?
  - No wire breaking in 2021 with isopropyl alcohol?
  - Wire removal work is necessary in this spring
- Discussion for drift chamber 2
  - With thicker cathode wires (Ag/Al 40→50~60μm)
  - Backup and better solution
  - Two years necessary for production, the current chamber will be anyway used until CDCH2 ready



- CDCH re-opened on 16/02
- During the short period with the chamber exposed to the cleanroom atmosphere T was 22-23°C and RH did not exceed 35%

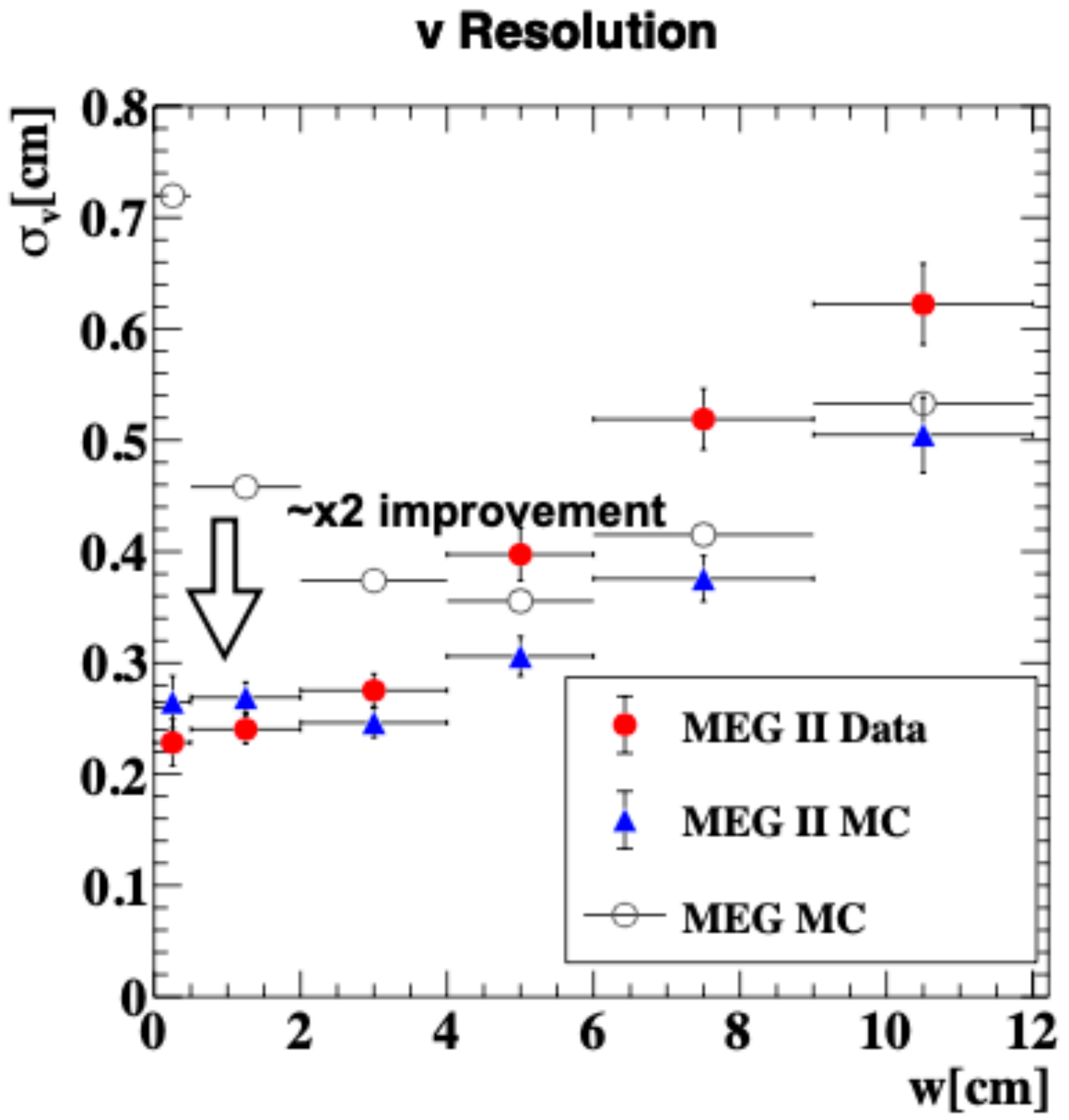
Sensitivity estimate from e+ 13aT2-1 宇佐見

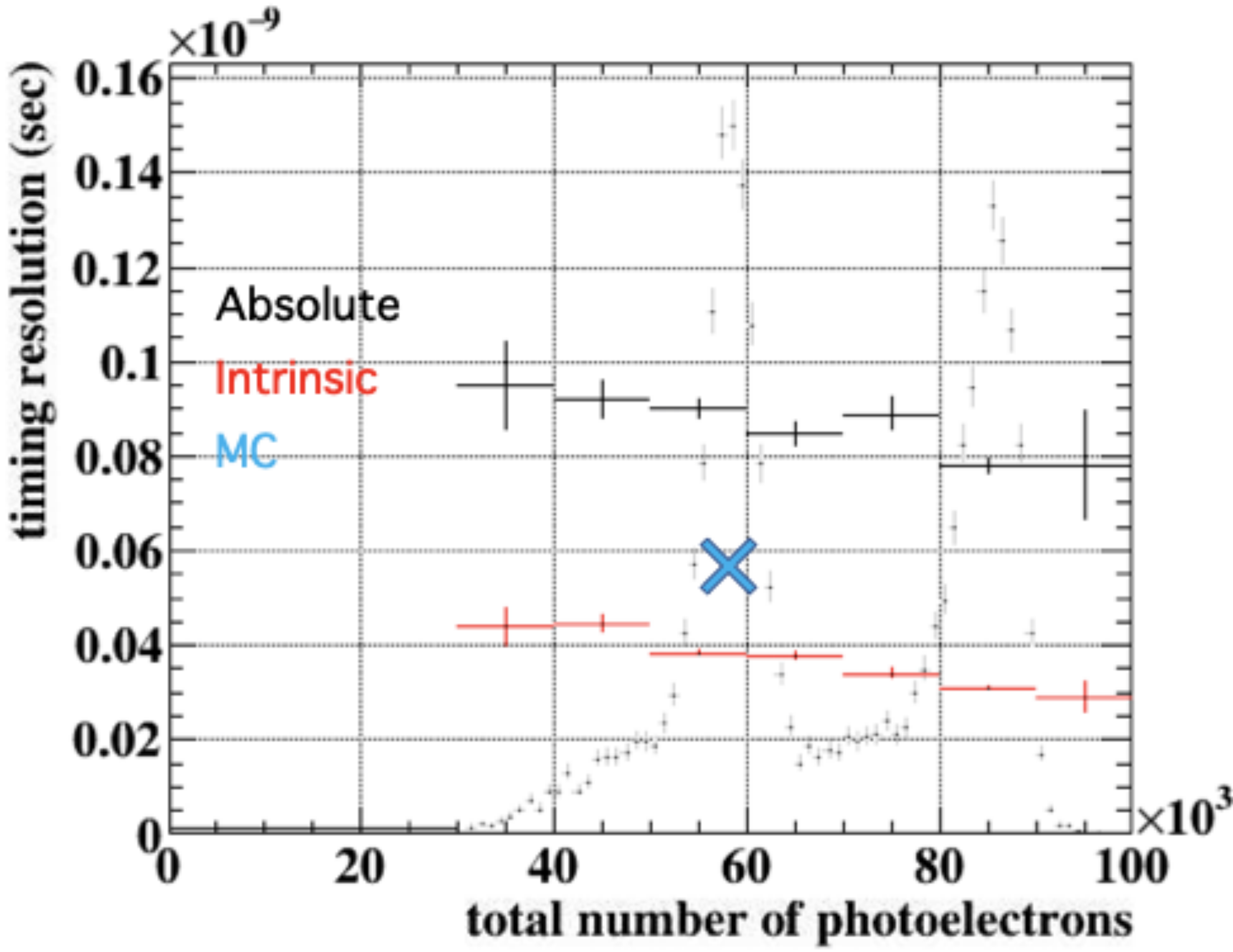
e+ reconstruction14aT3-7 内山

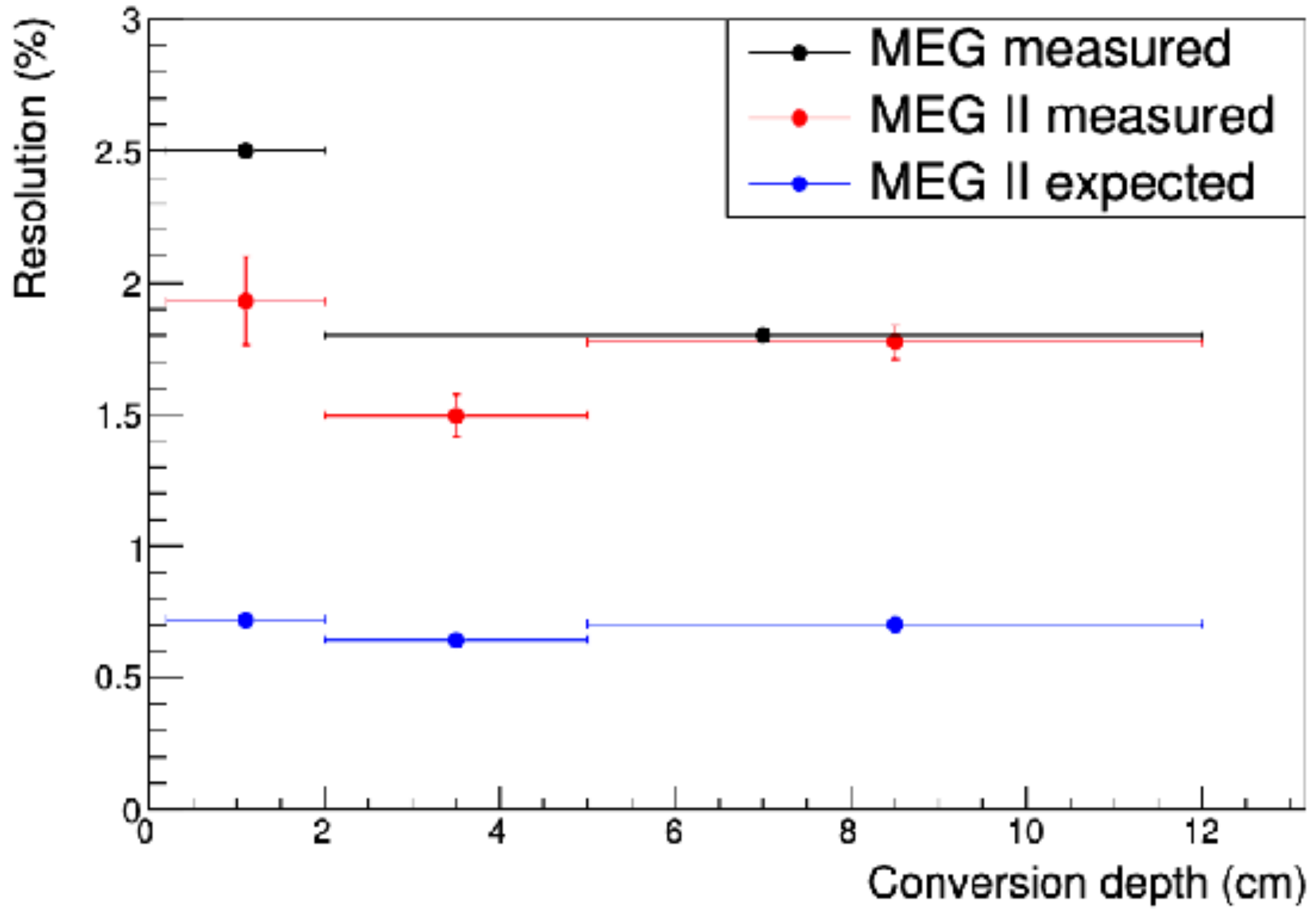
LXe performance

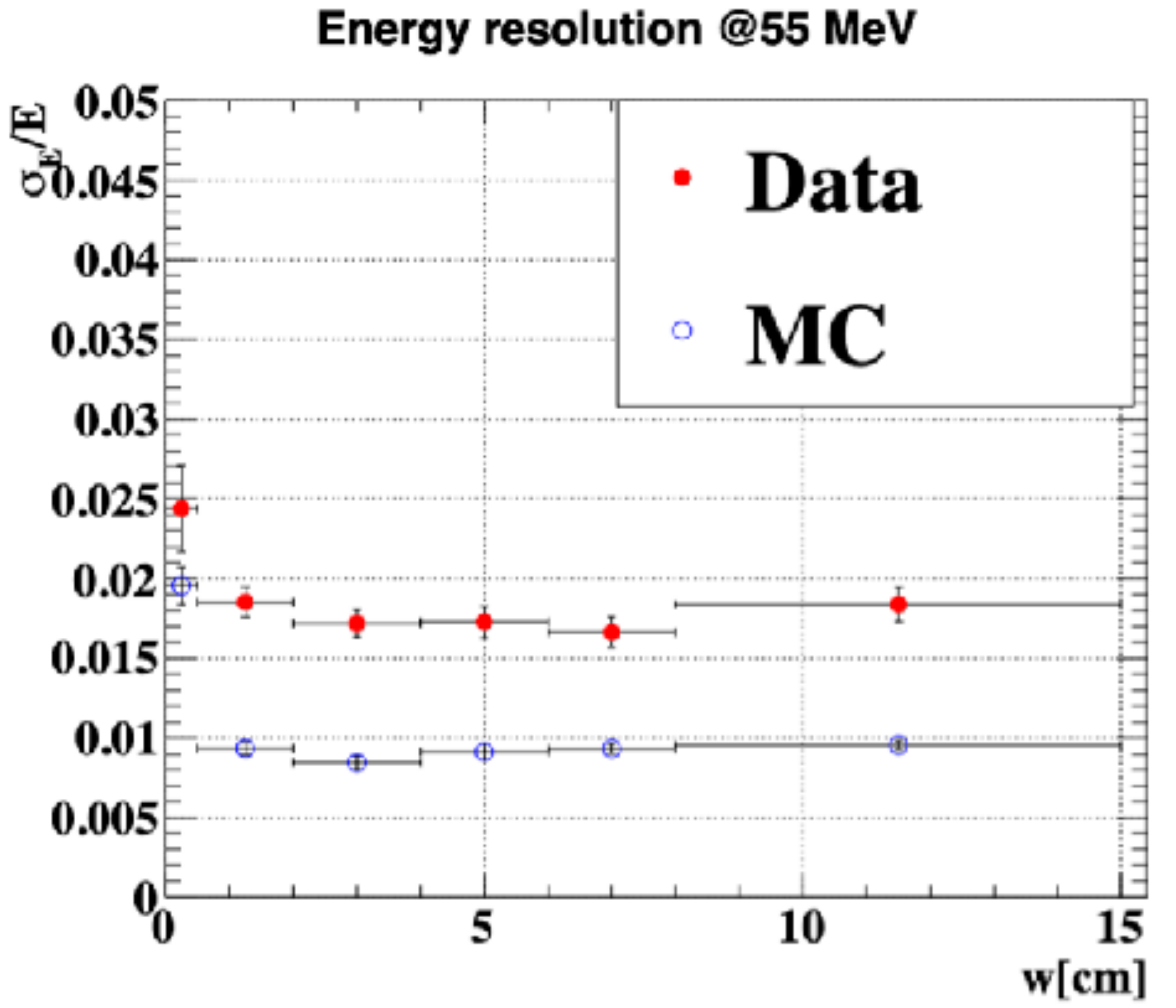
- Position resolution
  - almost consistent with MC expectation
- Time resolution 14aT2-3 恩田
  - 82 ps is still worse than MC expectation (57 ps)
- Energy resolution 14aT2-2 小林
  - worse than MC expectation
  - better than MEG at depth<2cm
- Prospects
  - Measurements done with a limited number of channels, and will be updated with full electronics
  - Calibration&algorithm still to be improved

14aT2-1 家城







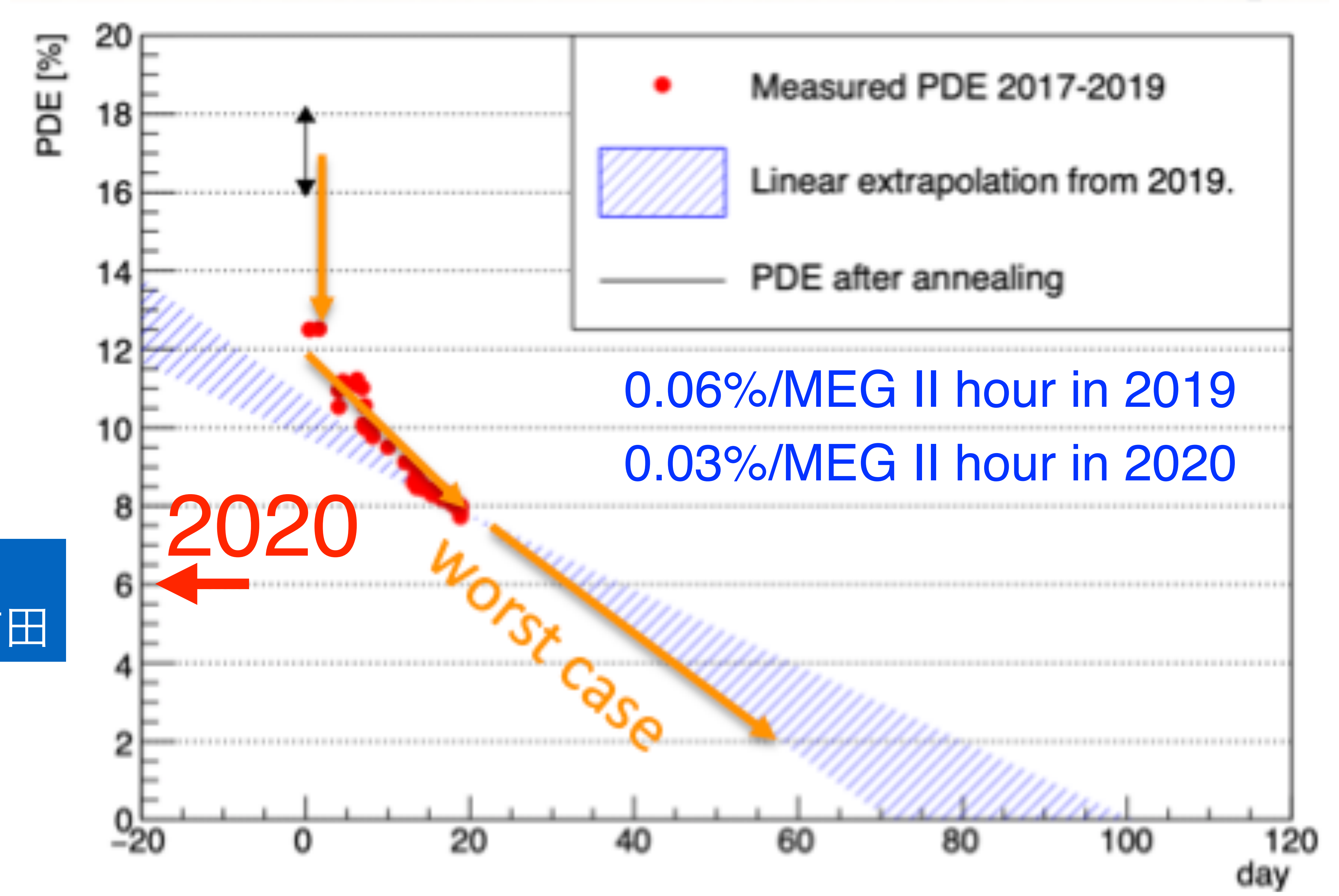


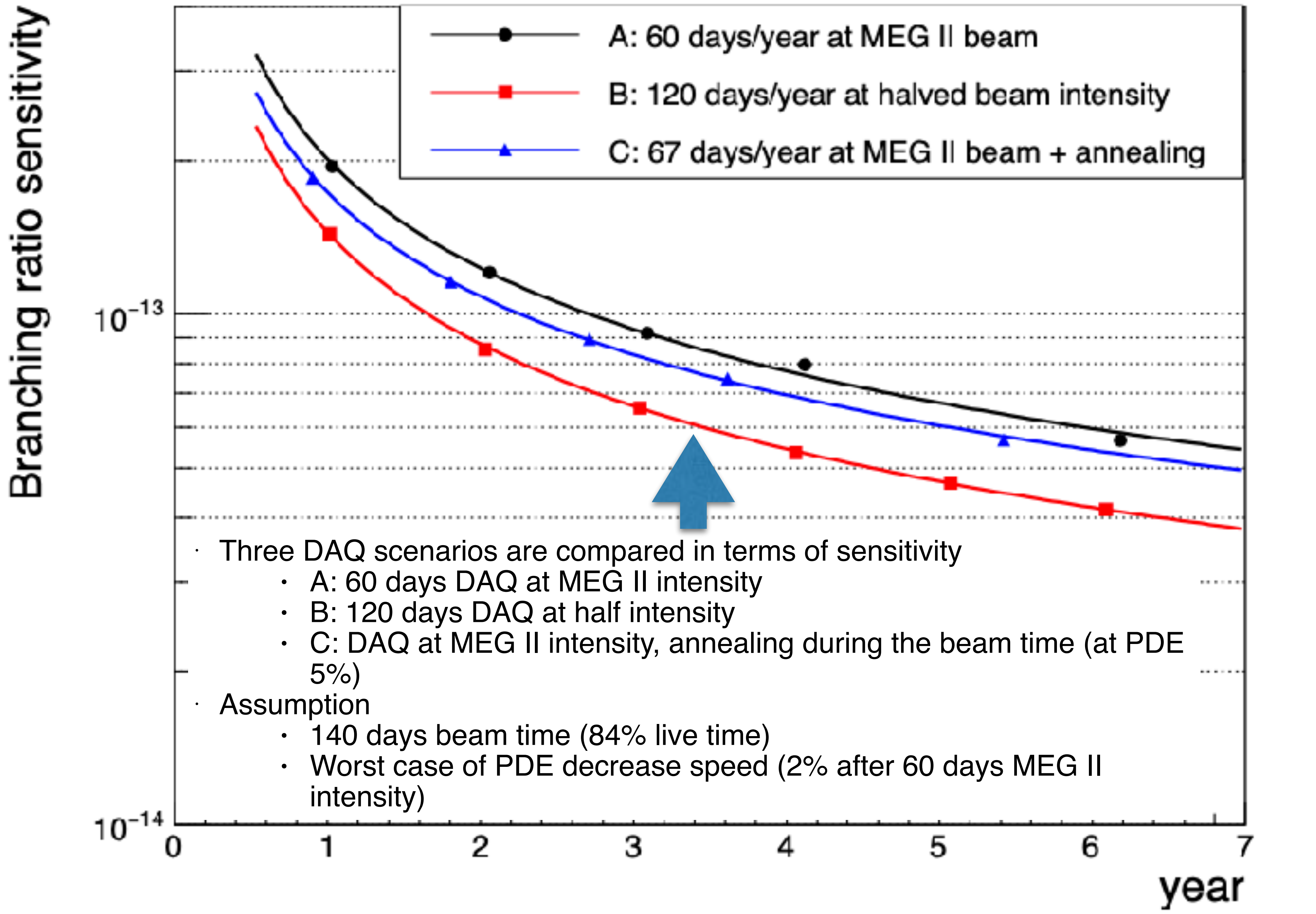
LXe issues

- MPPC PDE degradation under beam
  - critical to operate the LXe detector for long physics run
  - Annealing can recover the PDE completely

PDE lab. test
12pT2-9,10 島田、吉田

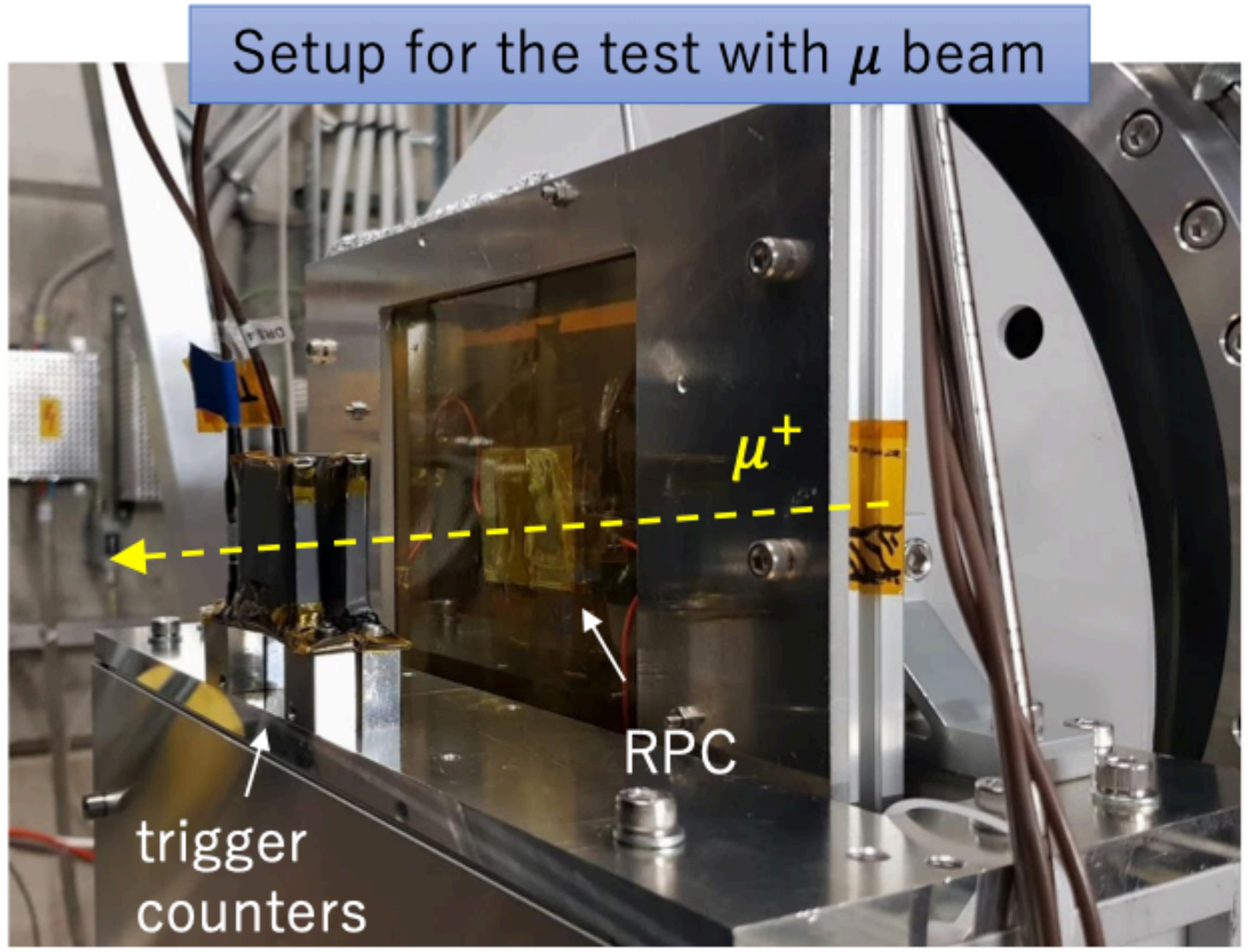
- Items to be checked
  - Is PDE degradation stopped at certain level above 0%?
  - Is PDE degradation speed getting slower and slower?
- Sensitivity update from LXe detector
  - Worst PDE decrease scenario suggests half beam intensity
  - This will be finalized with the full behavior of MPPC degradation
- Performance check with full electronics
  - Noise, sensor calib., uniformity check, energy scale, resolutions
  - CEX run will be done in 2021



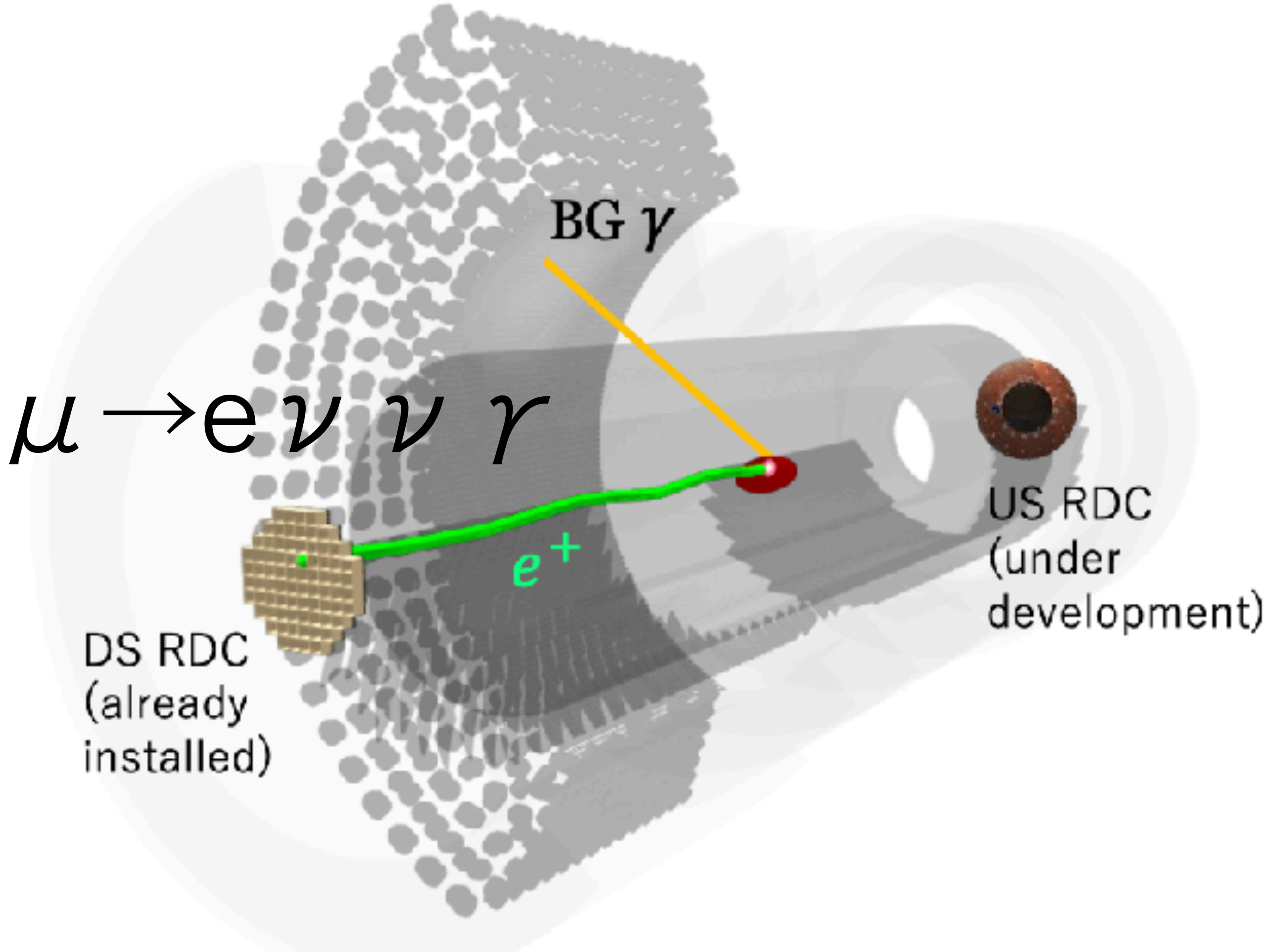


US RDC (RPC) beam test

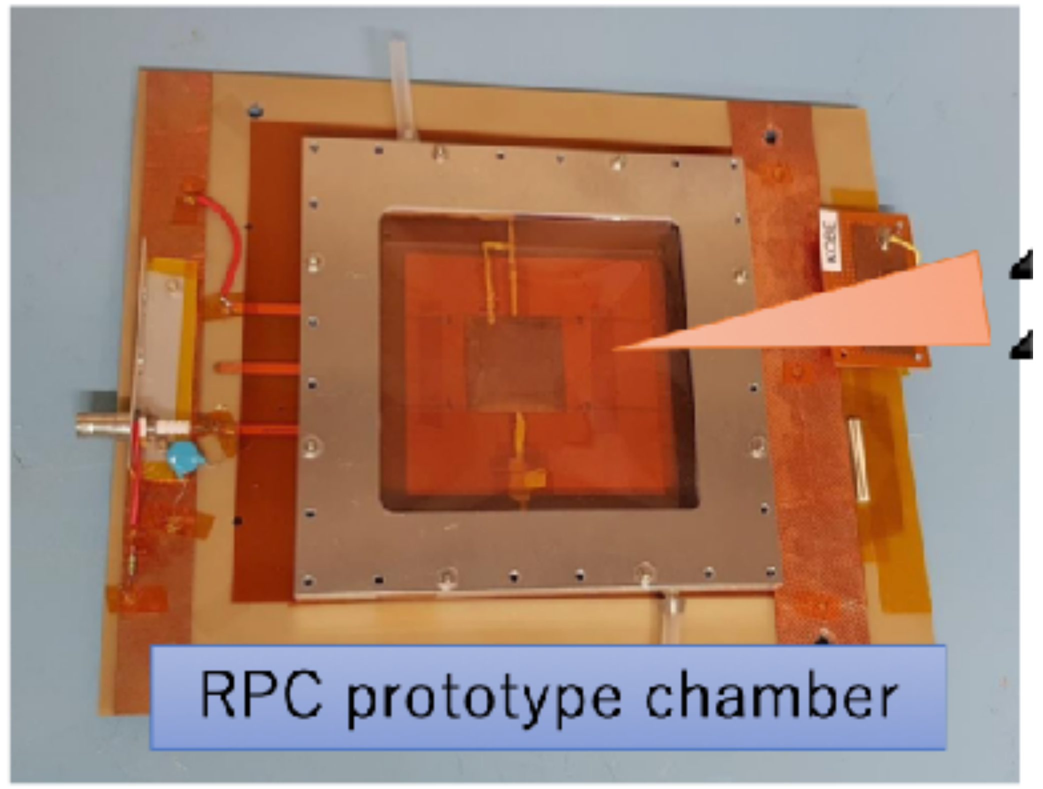
- RDC to identifies RMD backgrounds
- DS RDC : ready for the physics run
- US RDC : under development
  - Extremely low mass (<$0.001X_0$) because muon beam must penetrate it
  - Resistive Plate Chamber (RPC) with Diamond-Like Carbon (DLC) resistive electrodes is under development
  - Efficiency > 90%, σ_t<250 ps fulfilled

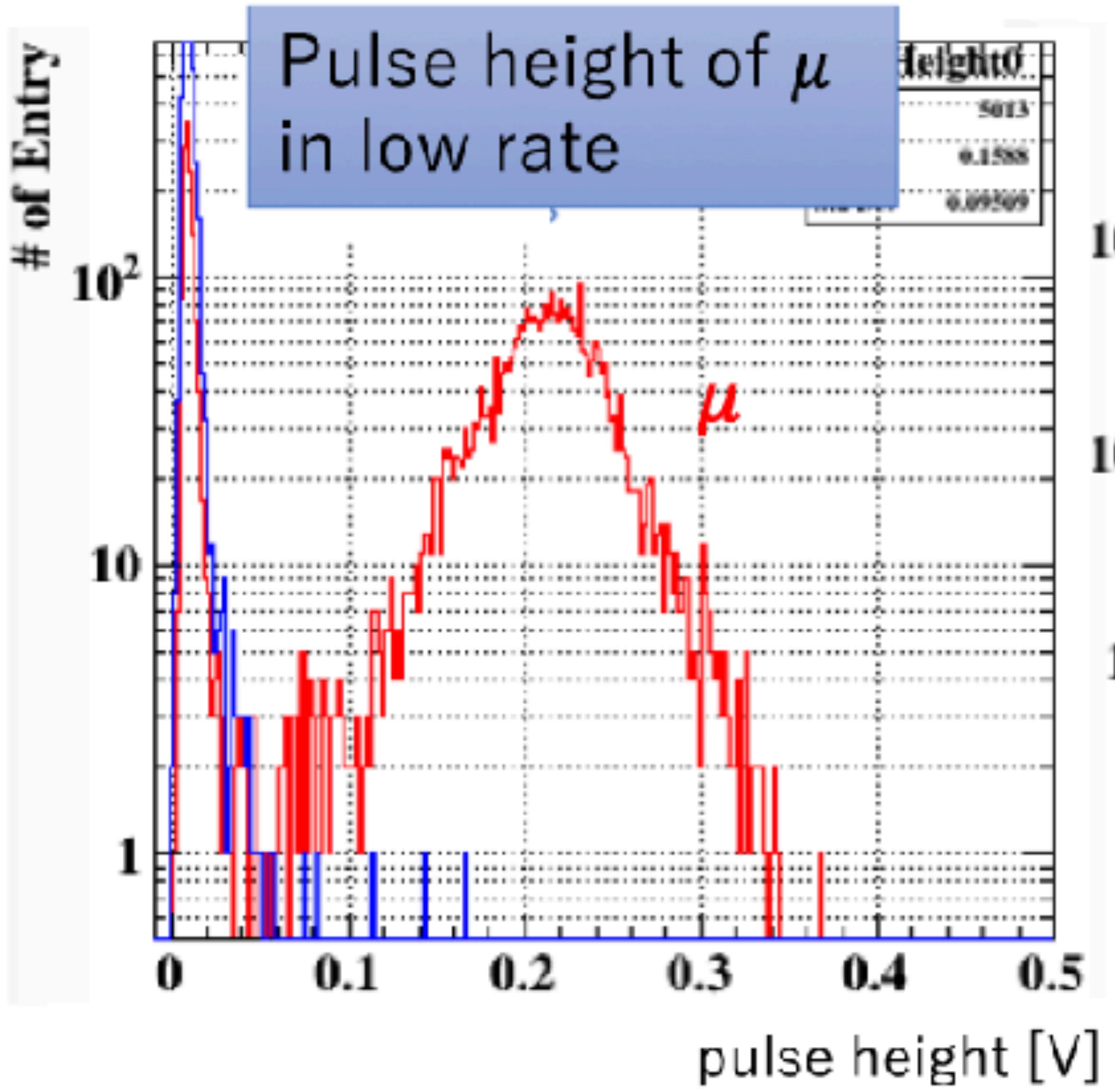


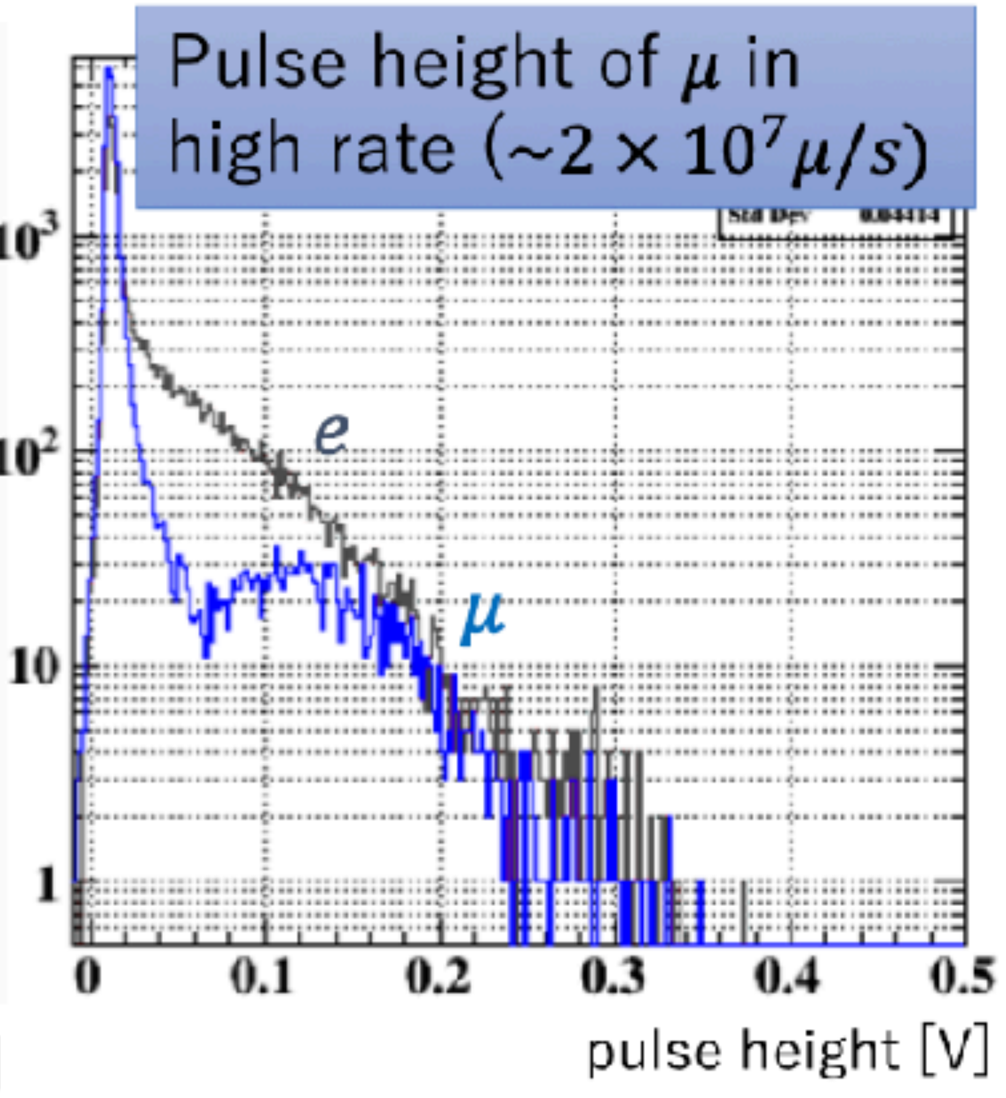
- Remaining concern
  - does it work under high rate μ beam?
- RPC beam test was performed
  - muon signal was successfully obtained, and voltage drop is also observed as expected.
- The design will be finalized based on these results



RPC beam test
13aT2-2,3 山本、大矢

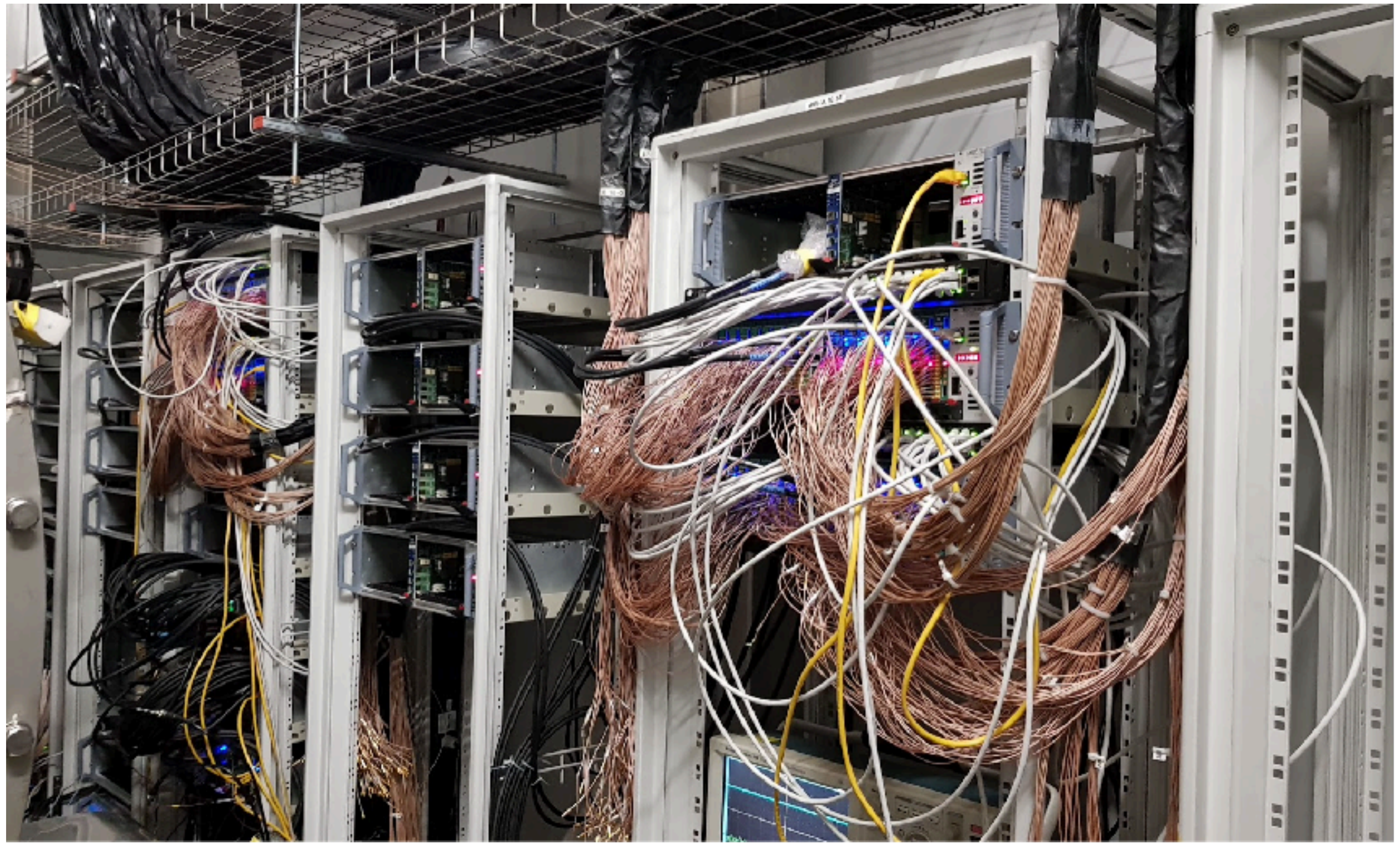






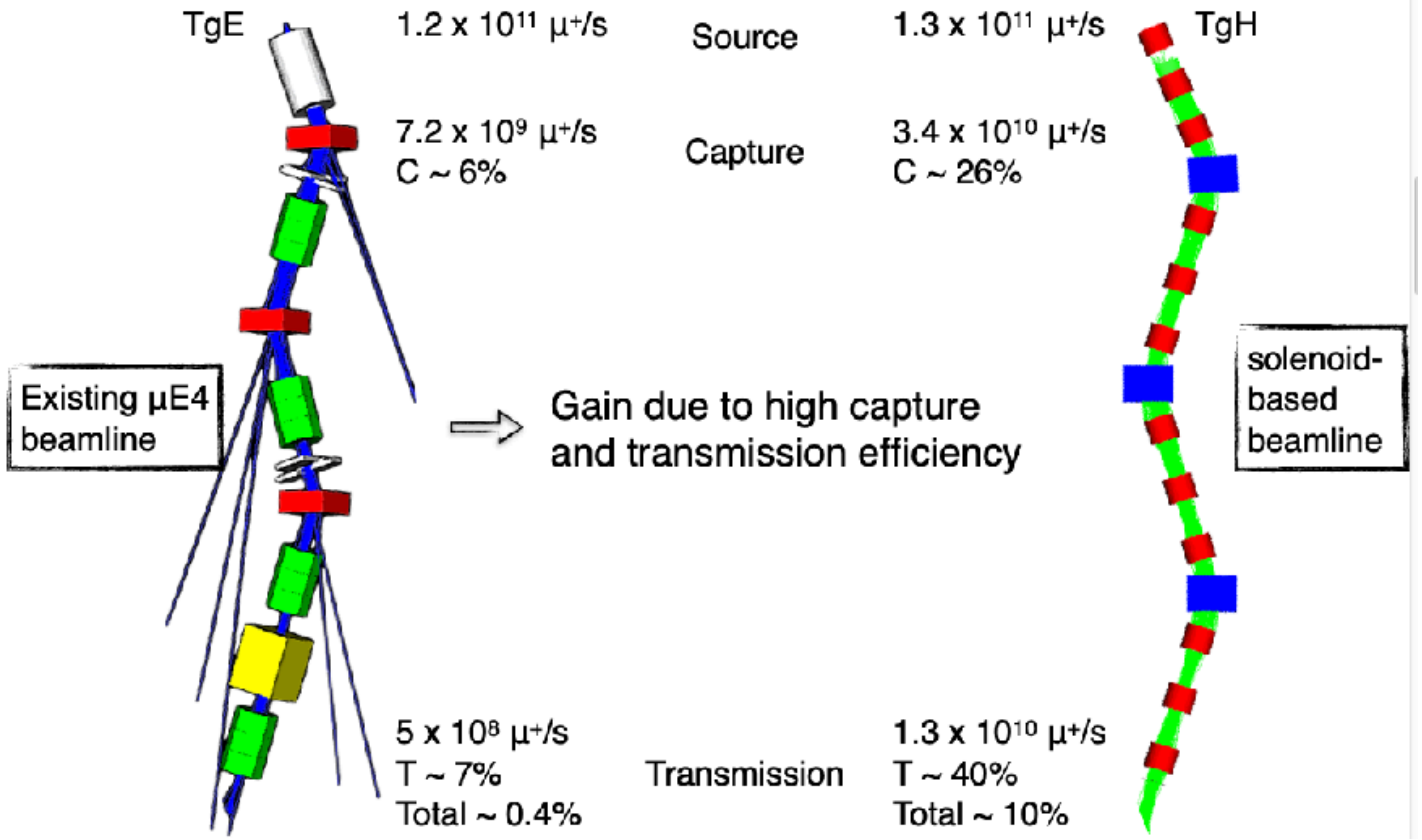
2021 run

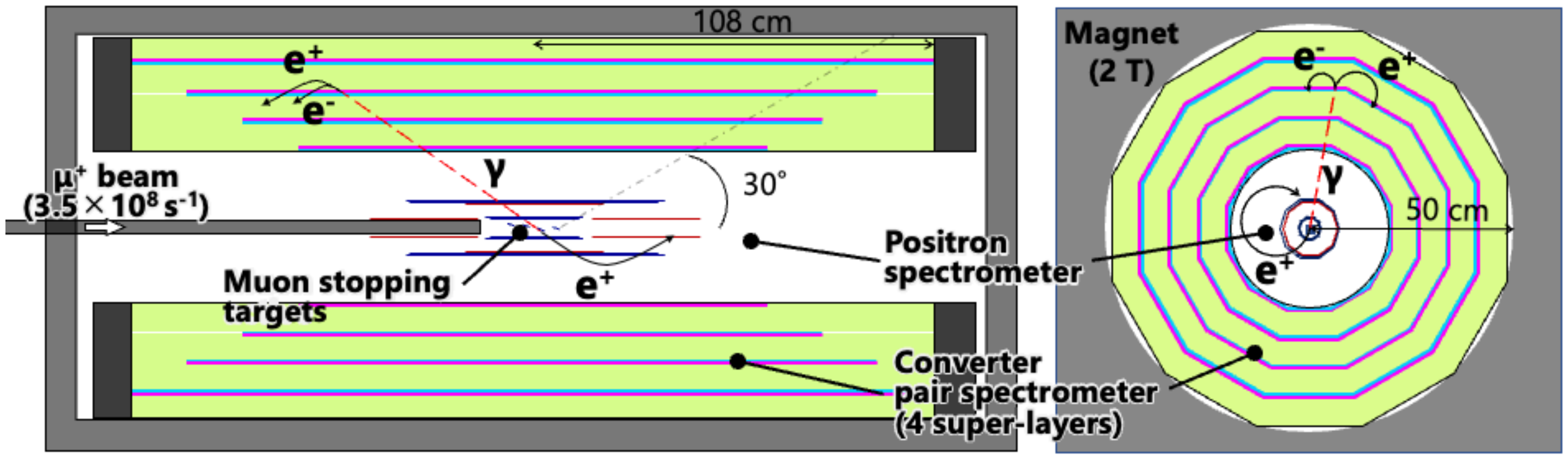
- Full electronics mass production finishes March 2021
  - Installation & setup for 3 months (March - May)
- June - July : Each detector commissioning
- Aug - Nov : MEG II trigger setup
  - LXe MPPC PDE study
  - CDCH stable operation
  - CDCH2 construction
- Dec : Engineering/physics run



After MEG II

- High Intensity Muon Beam project (HiMB) at PSI
  - 10^{10} μ^+/s (100× improvement)
  - CDR by end of 2021
  - Implementation during 2027/2028
  - Science Case workshop 6-9 April 2021
- Future μ→eγ experiment for CLFV
  - Goal: Br(μ→eγ) ~10^{-15}
  - Discover new physics and precision measurements
  - Detector R&D to make maximum use of HiMB
  - Resolution improvements
    - Calorimeter → converter + pair spectrometer
  - High rate tolerance
    - Drift chamber → Silicon detector
- Possible to measure μ→eee at the same time

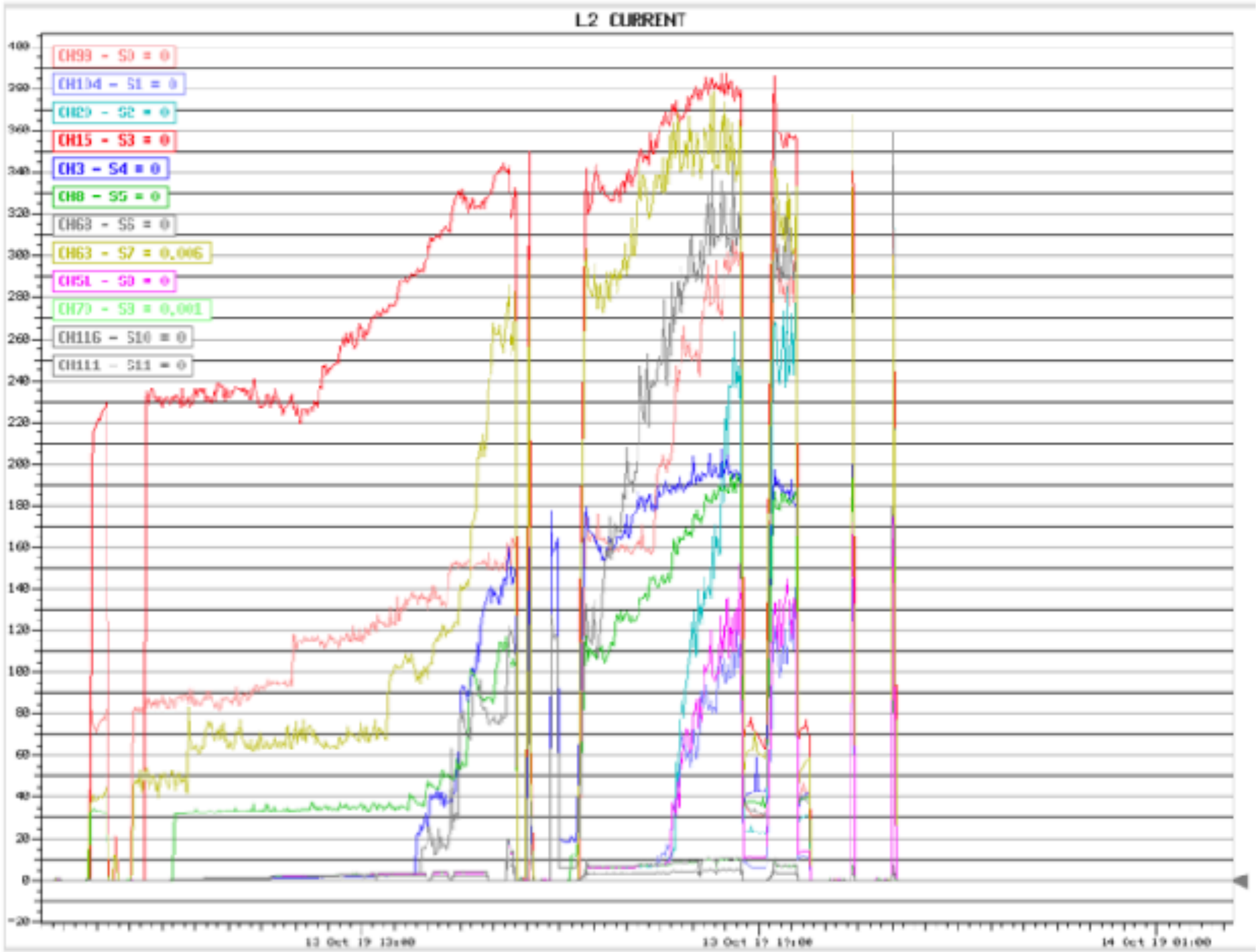




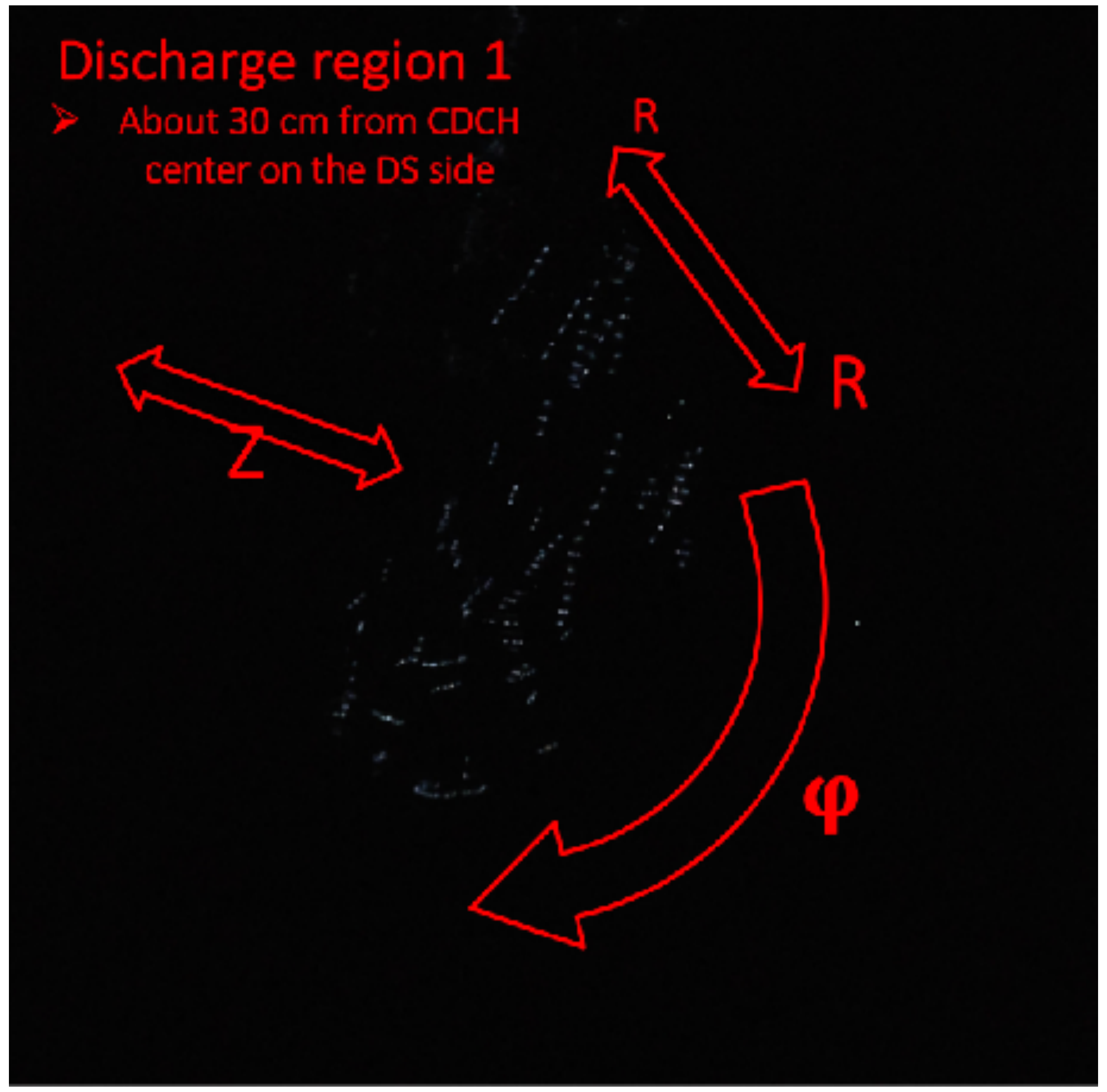
Summary

- All the MEG II detectors were tested under MEG II intensity
- The full electronics will be produced in March 2021
- PSI accelerator beam time in 2021 is decided, and we will concentrate on each sub-detector preparation for full electronics, and performing engineering run followed by physics run.
- There are several issues from each sub-detector for the physics run, but we will try to solve these problems to start the MEG II experiment this year

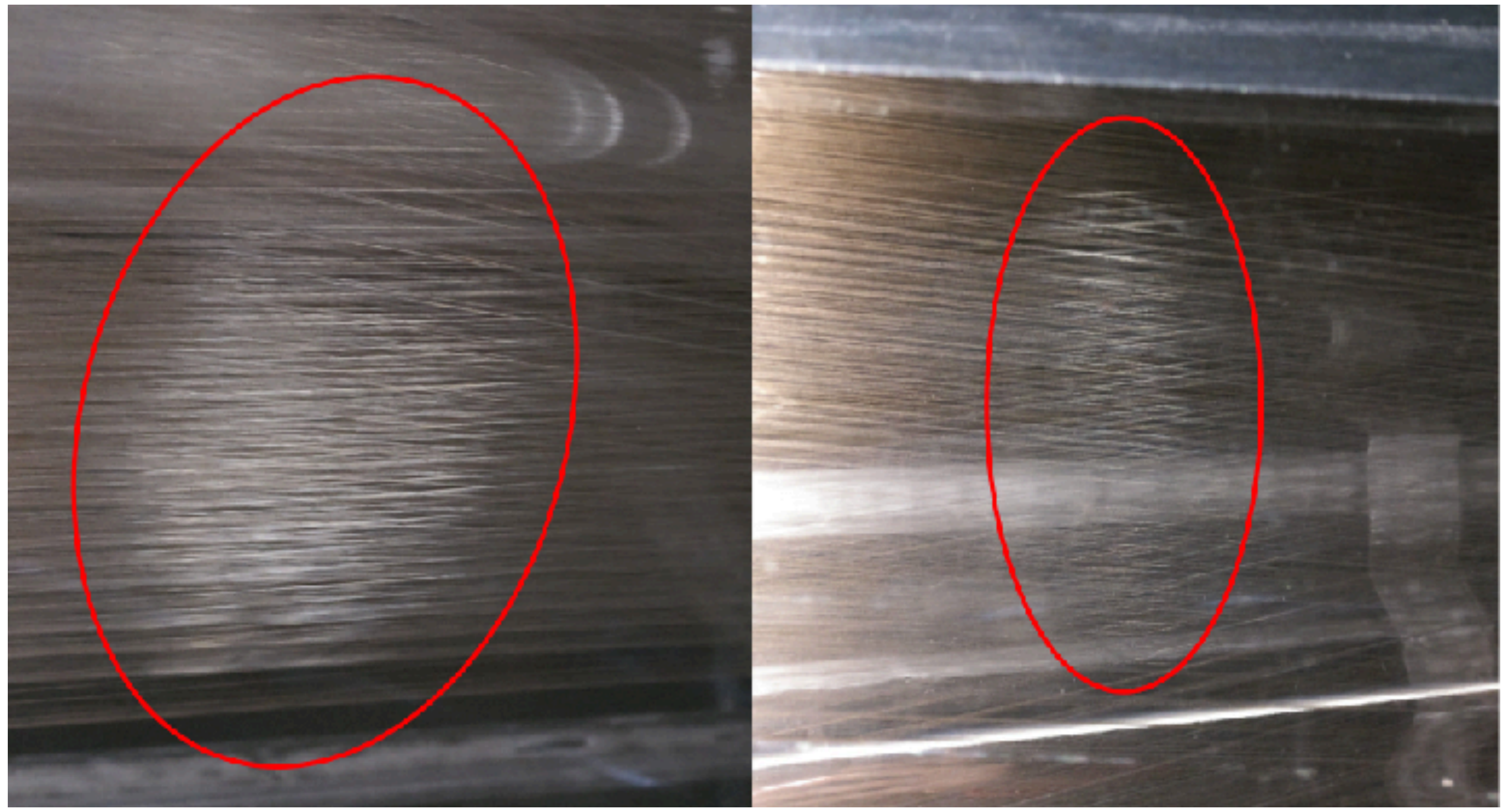
High current at CDCH



- large currents up to 300μA

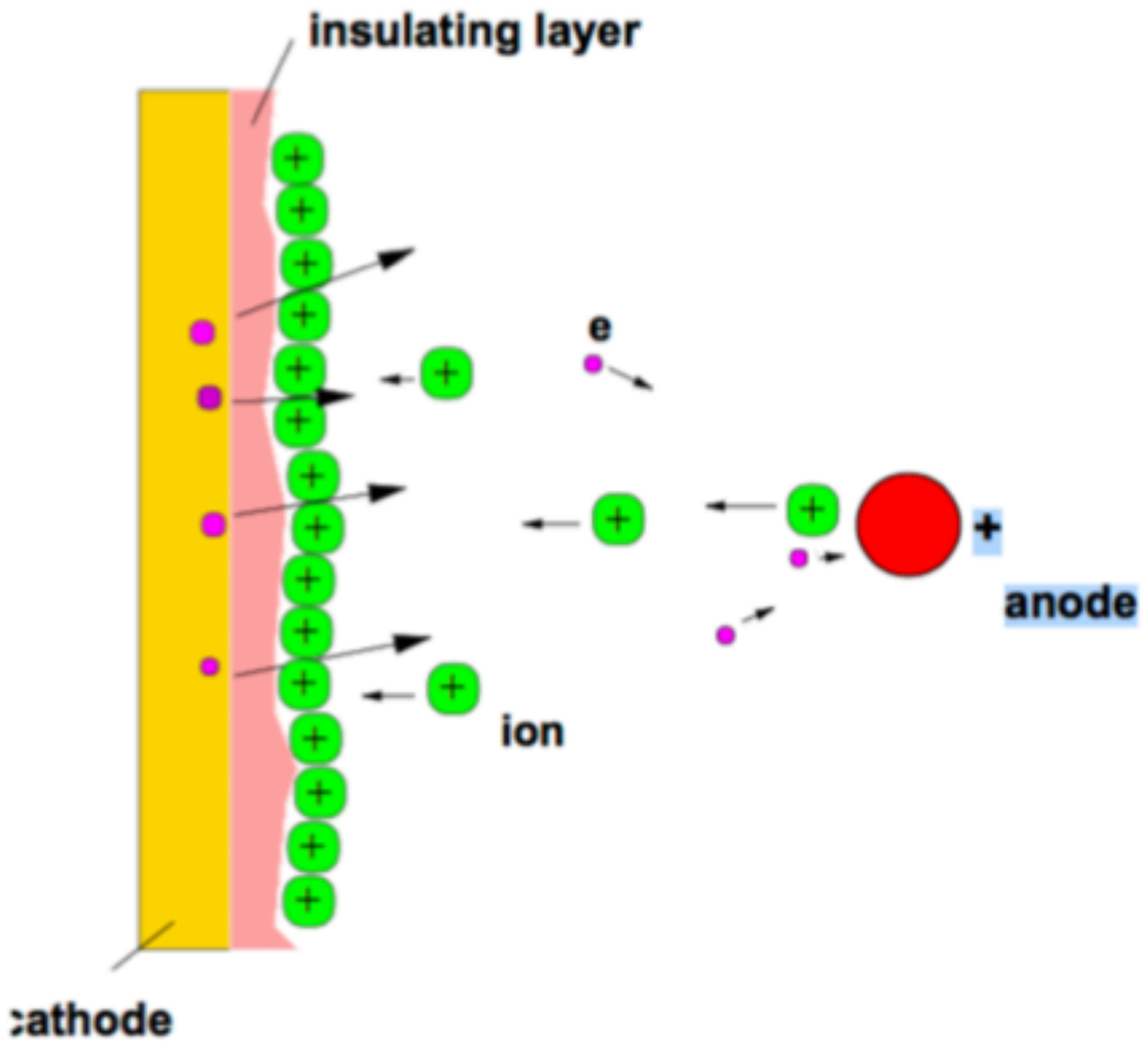


- Carbon fiber support replaced with plexiglass to see discharge by eye
- Succeeded in observing the corona discharge

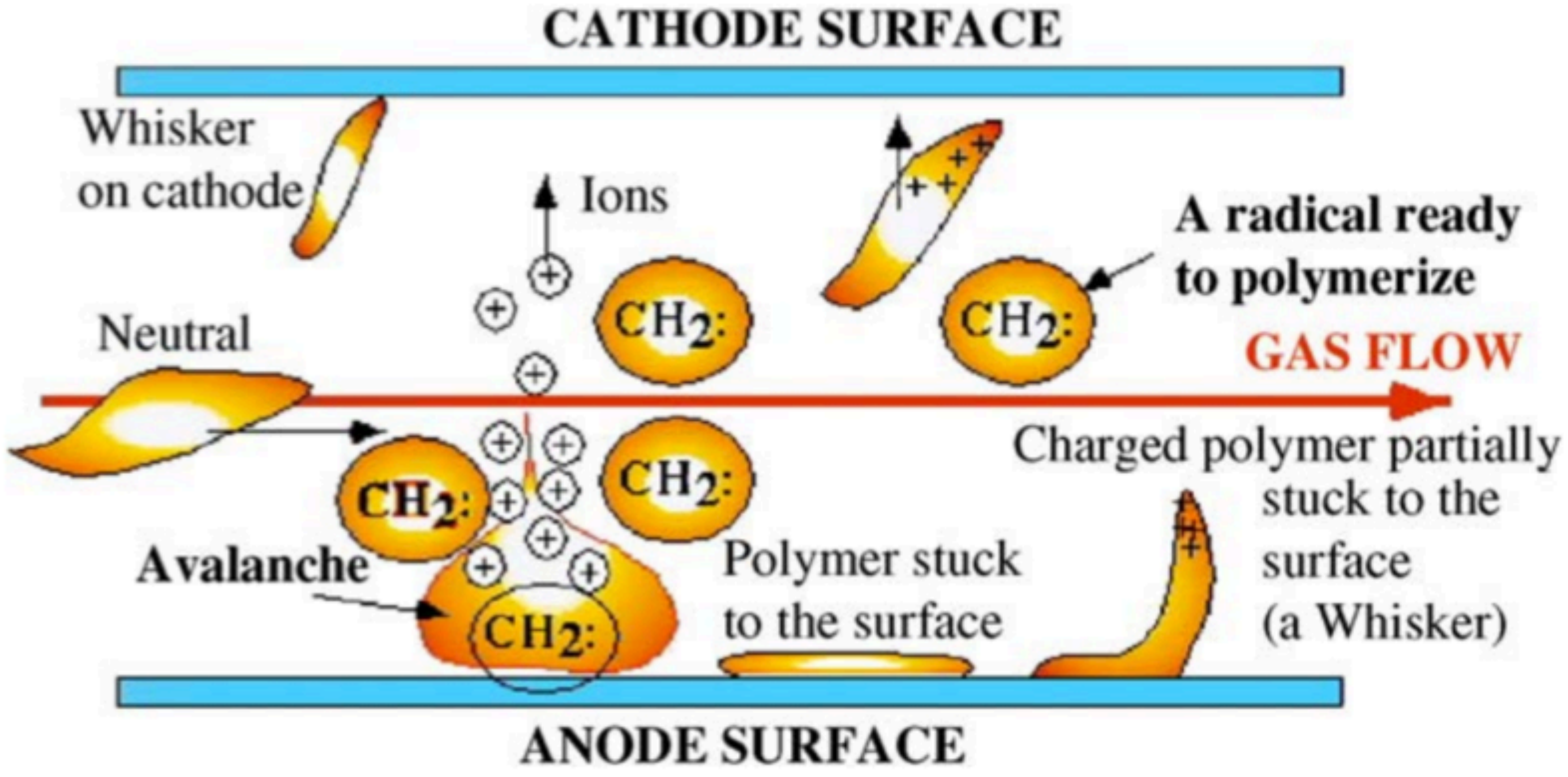


- Discharges are always correlated with whitish regions on wires
- Literature studies suggest
  - Corona discharges and Malte effect can be mitigated with addition of CO2, oxygen, water, alcohols and methylal

Malter effect and free radical formation



Malter effect

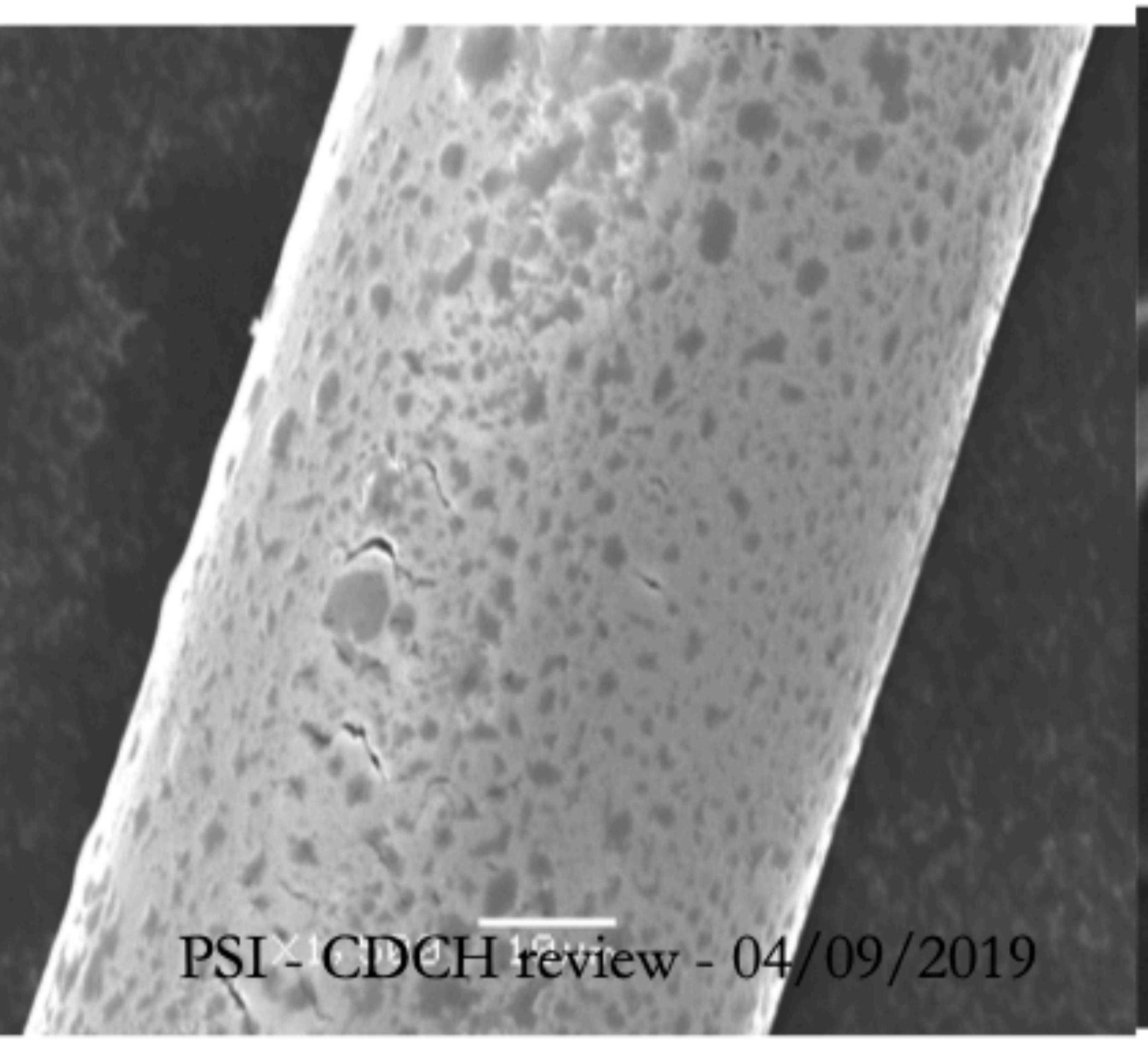


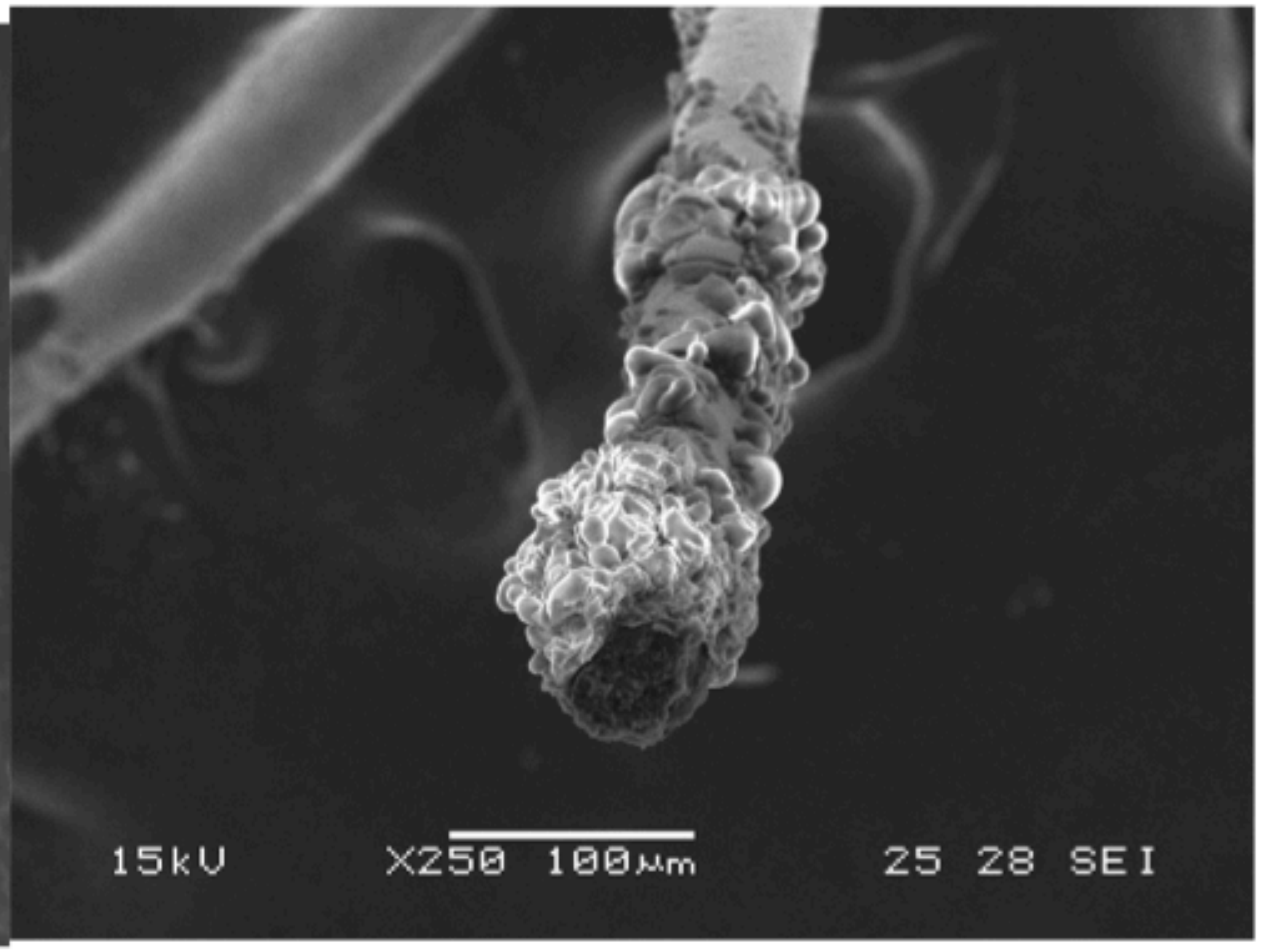
Free radical formation

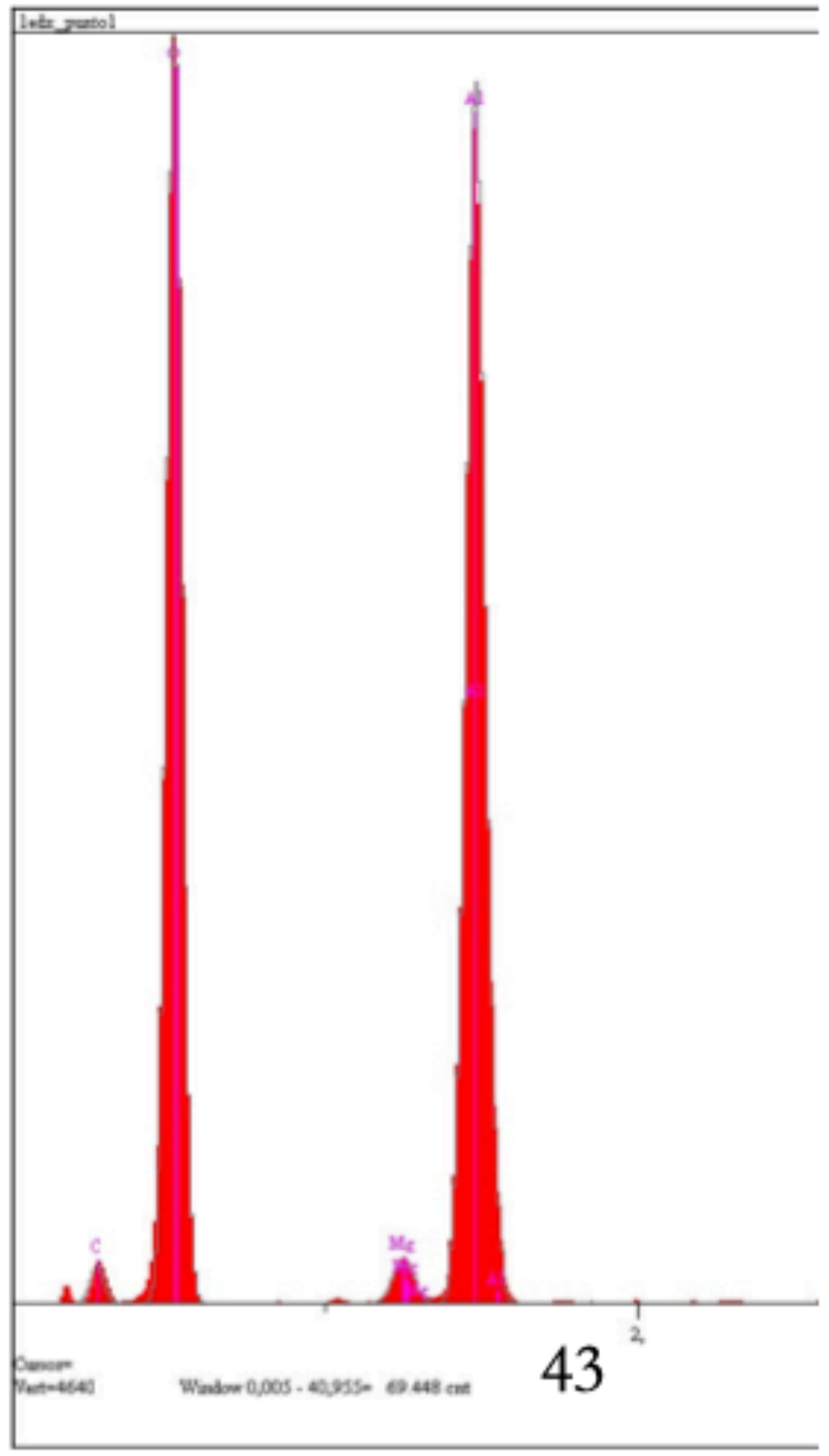
- Polymerization
  - fragmentation of chamber gas molecules can form free radical which deposits on wire surfaces
  - Charged polymer can be stuck to the surface (like Malte effect) → induce current
- Oxygen
  - can be radical in plasma under muon beam, and can attack the polymer (plasma cleaning)
- Isopropanol (Water)
  - can mitigate the surface charge deposit, but can not remove the polymer

Humidity effect

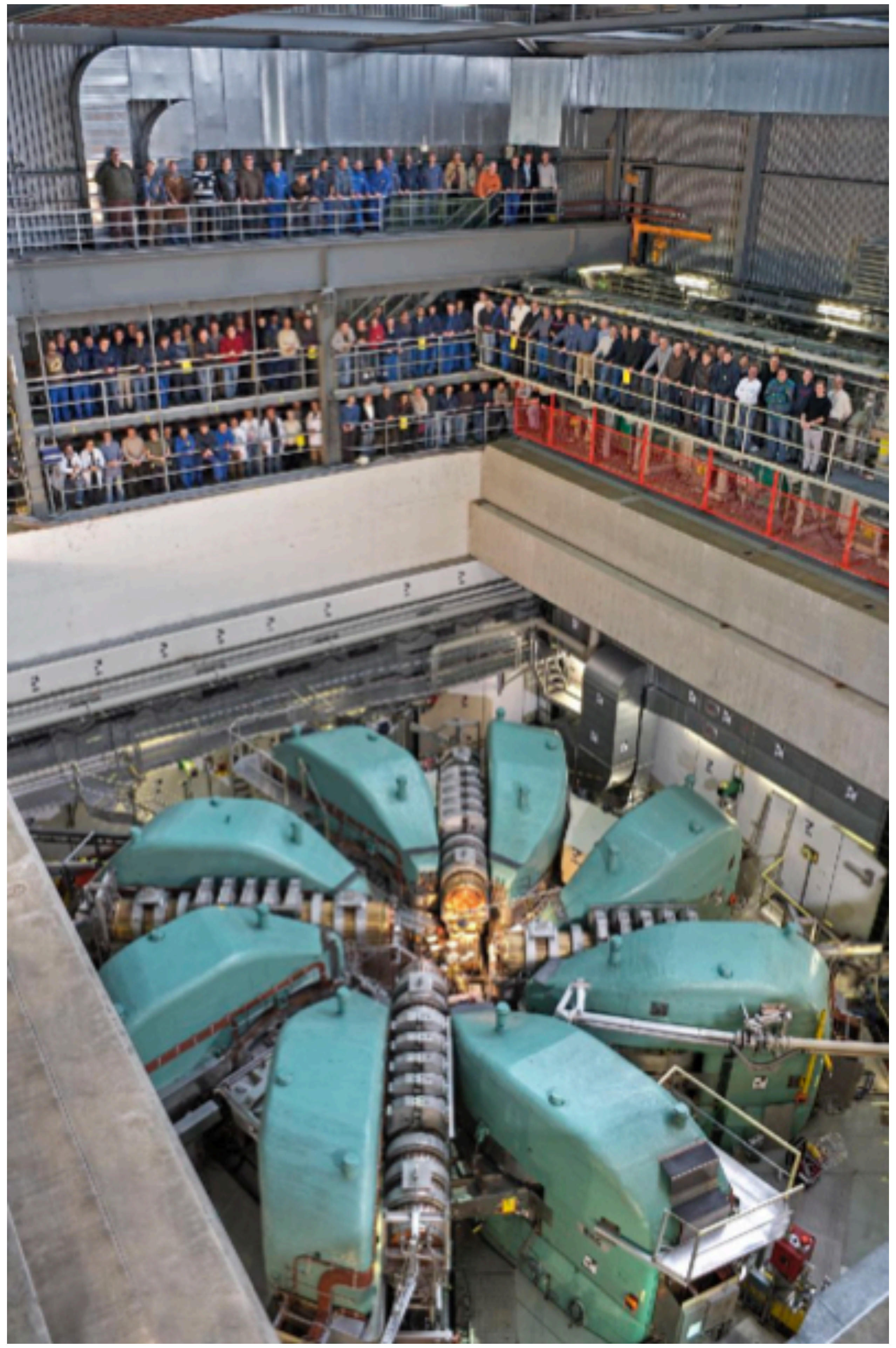
- Test were performed in Lecce and in Pisa
  - Aluminium wires were immersed or sprayed with demineralized water and with 3% water solution of NaCl
  - In all cases induced wire breaking were identical to the ones observed on the chamber
  - The salt near the wire edge contains Al and O: it could be aluminium oxide or aluminium hydroxide



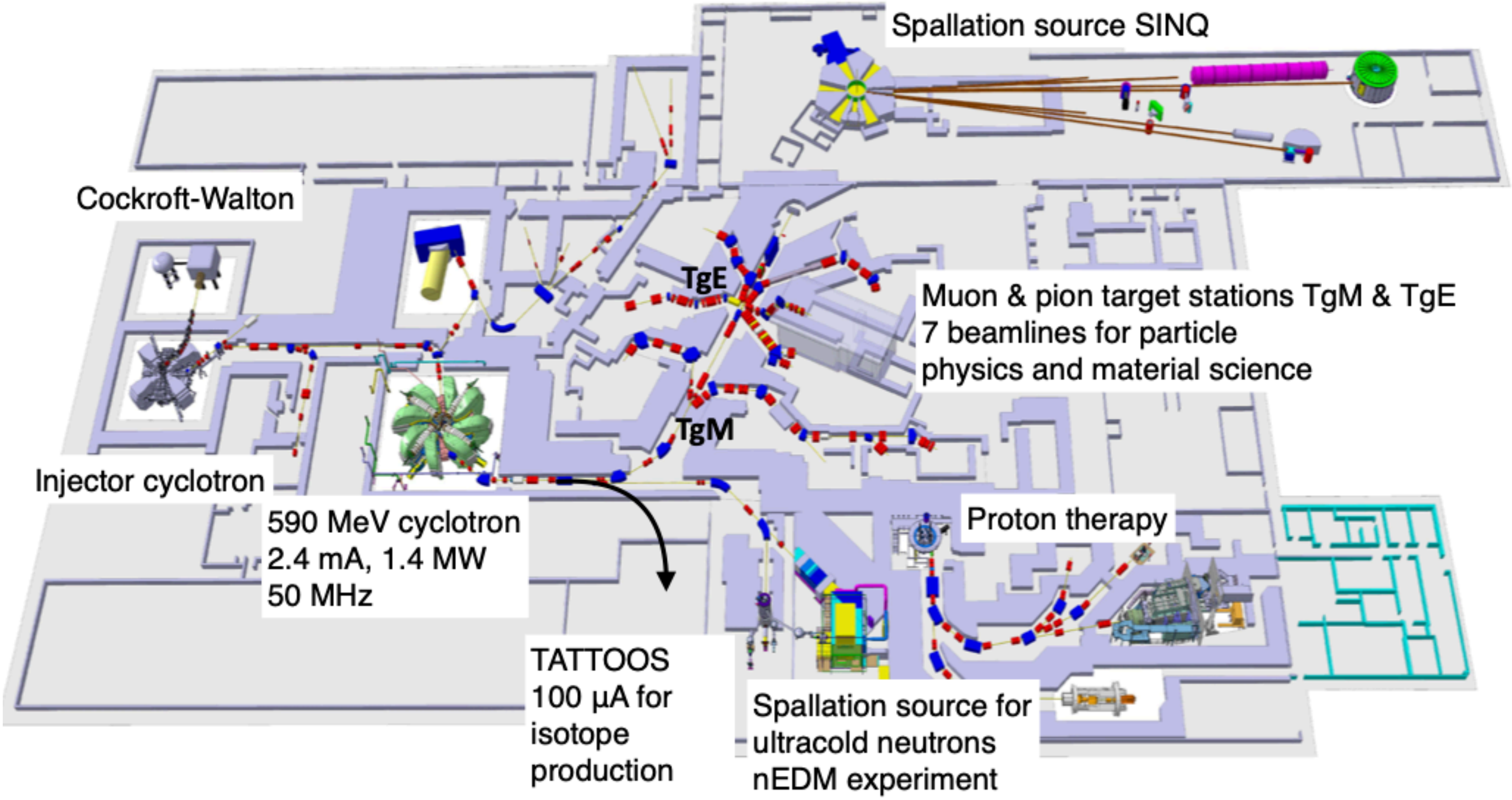




$$\mathrm{Al} + 3\mathrm{Cl}^- \longleftrightarrow \mathrm{AlCl_3} + 3e^-$$
$$\mathrm{AlCl_3} + 3\mathrm{H_2O} \longleftrightarrow \mathrm{Al(OH)_3} + 3\mathrm{H}^+ + 3\mathrm{Cl}^-$$



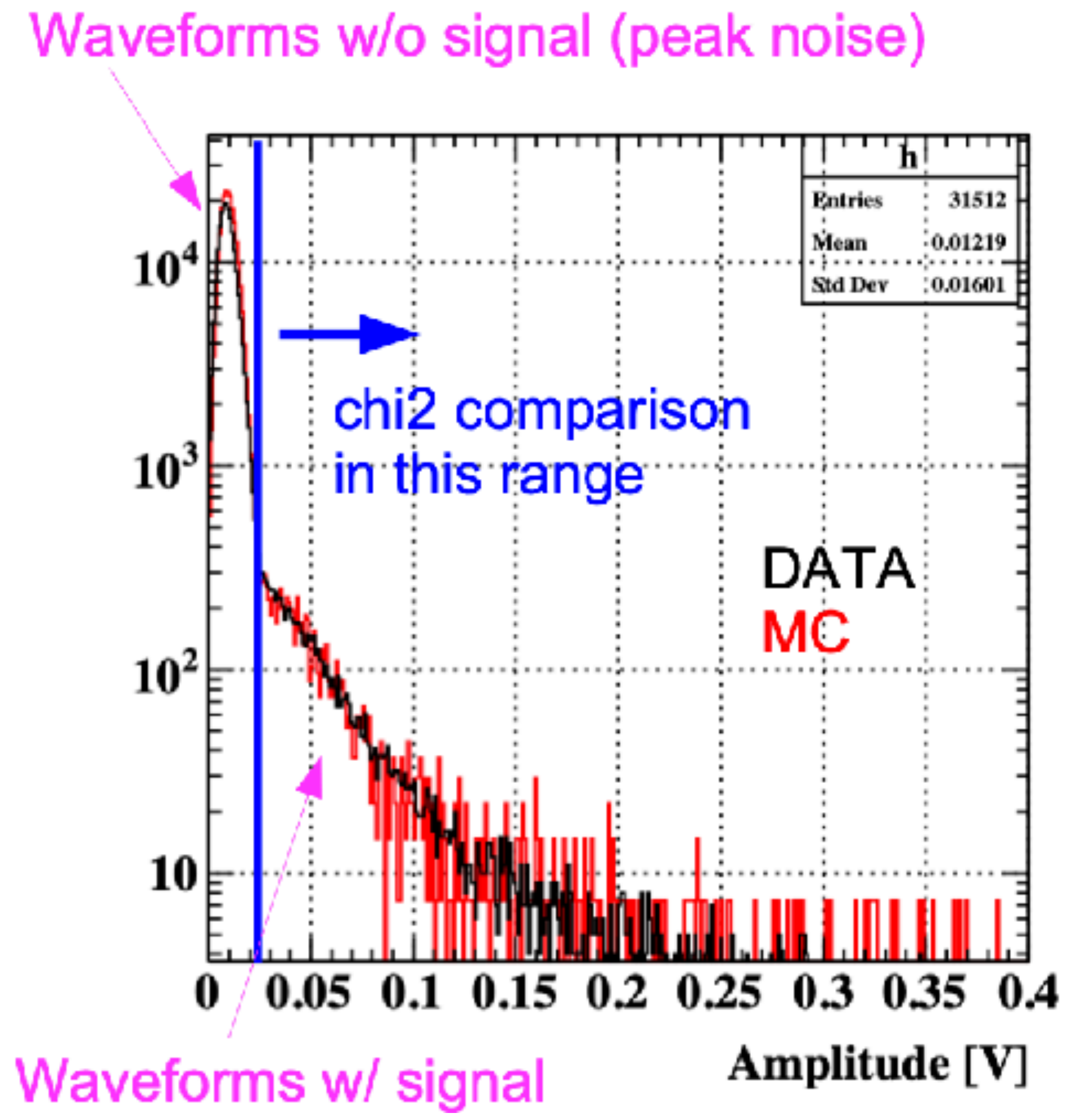
PSI accelerator

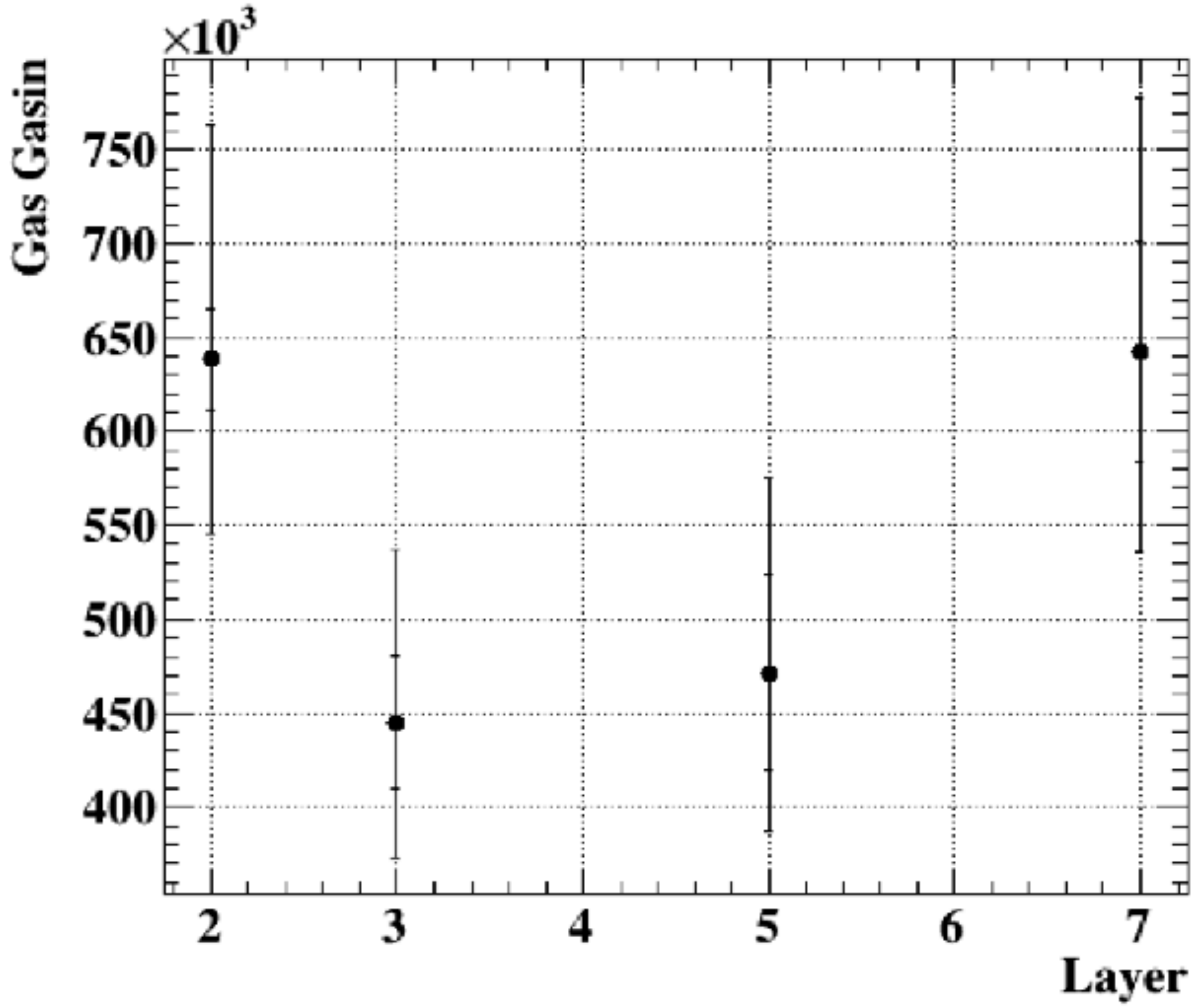


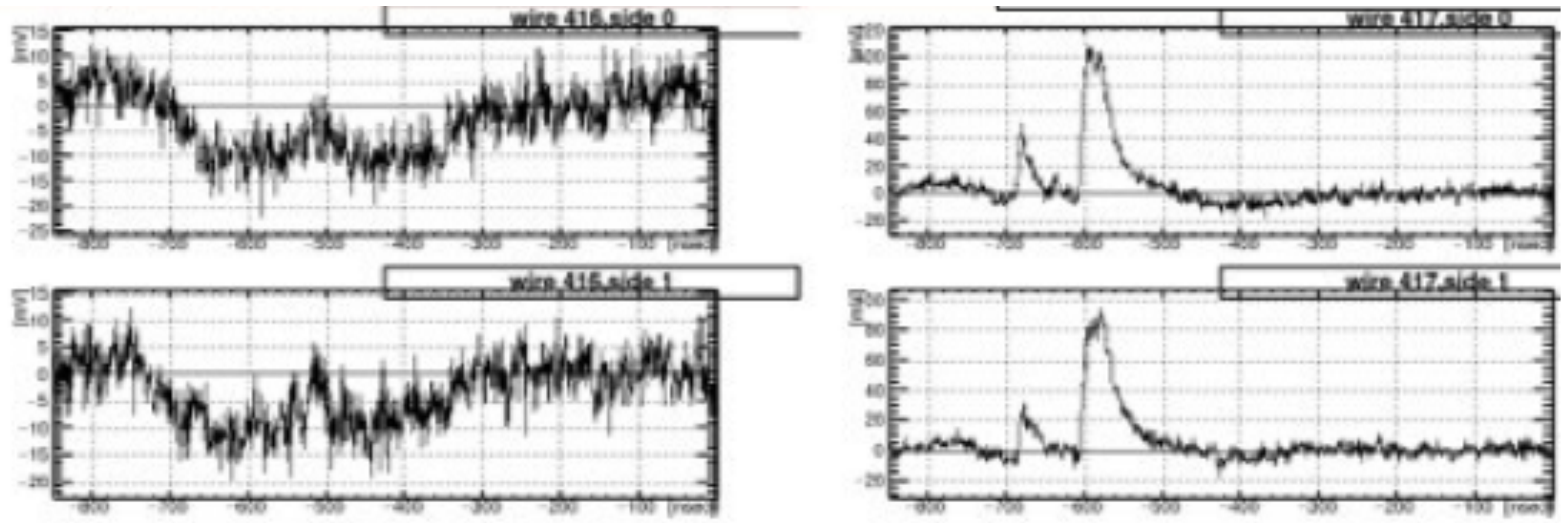
- CHRISP - Swiss Research InfraStructure for Particle physics at Paul Scherrer Institute in Switzerland
- World most intense DC muon beam available : > $10^8 \mu^+/s$
- High precision particle physics experiments complementary to the experiments at the highest energies at CERN's LHC
- There is an upgrade project, HIMB (High Intensity Muon Beam) project, 10^{10} μ/s
    - Science case workshop 6-9 April 2021
    - Conceptual Design Report by end 2021
    - Implementation during 2027/2028 during 16-months HIPA shutdown

CDCH performance

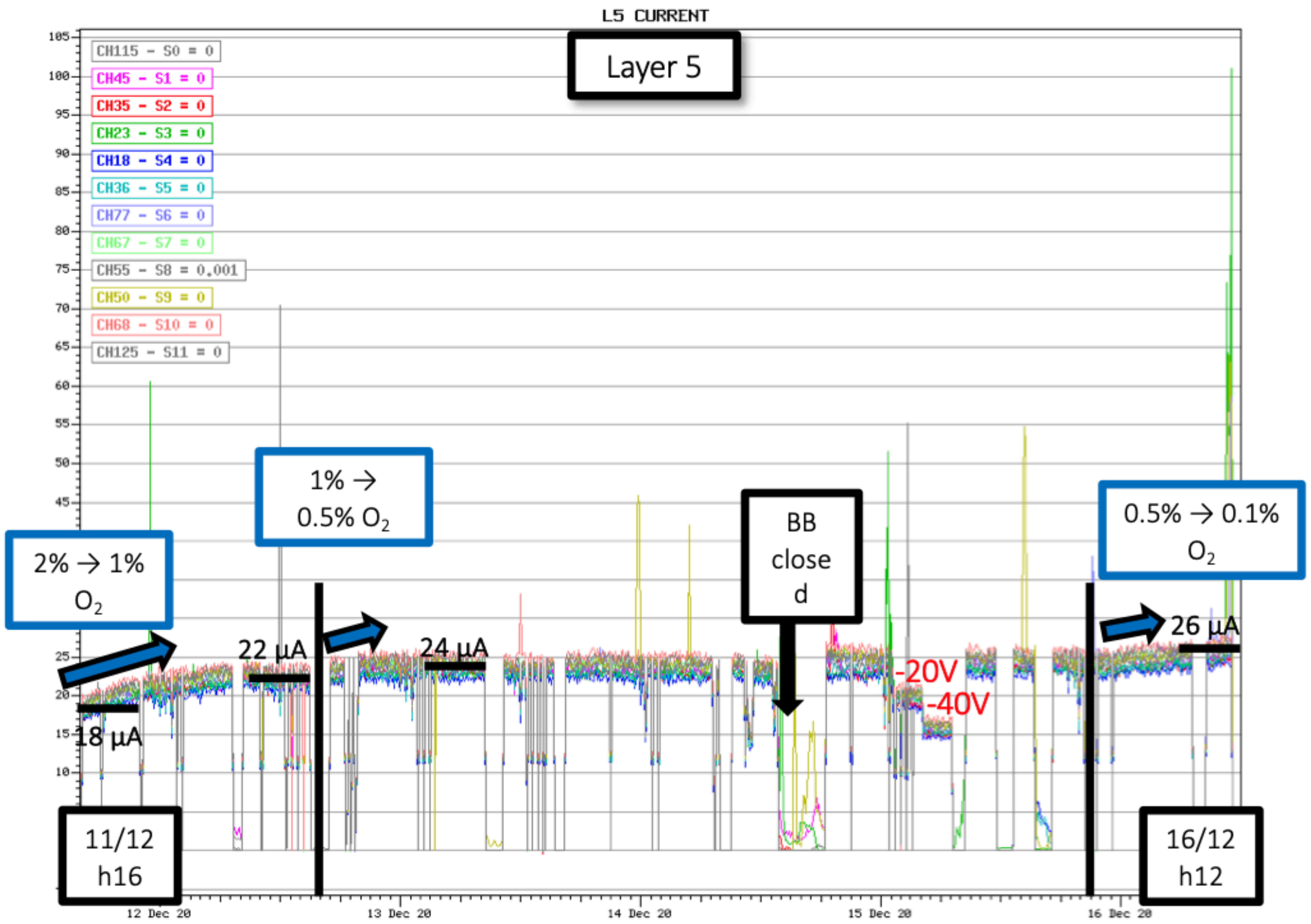
- Gas gain is obtained from total gain (from data) divided by FE gain measured by prototype
  - Total gain = 8.6±0.7 [mV/e]
  - FE gain = 0.12 [mV/fC]
- Limited number of readout channels prevent a robust estimated of the reconstruction performances





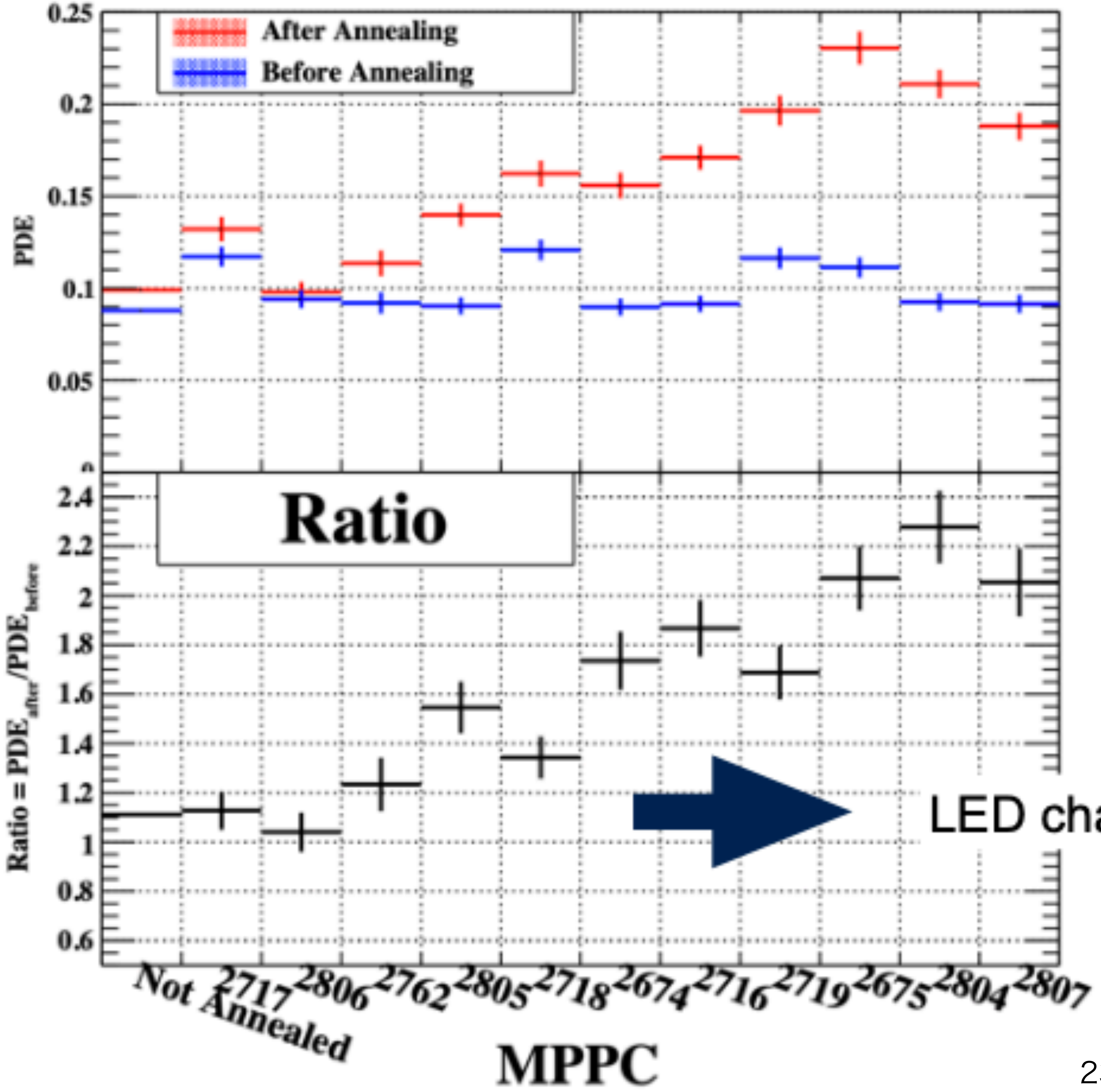


CDCH high current issue



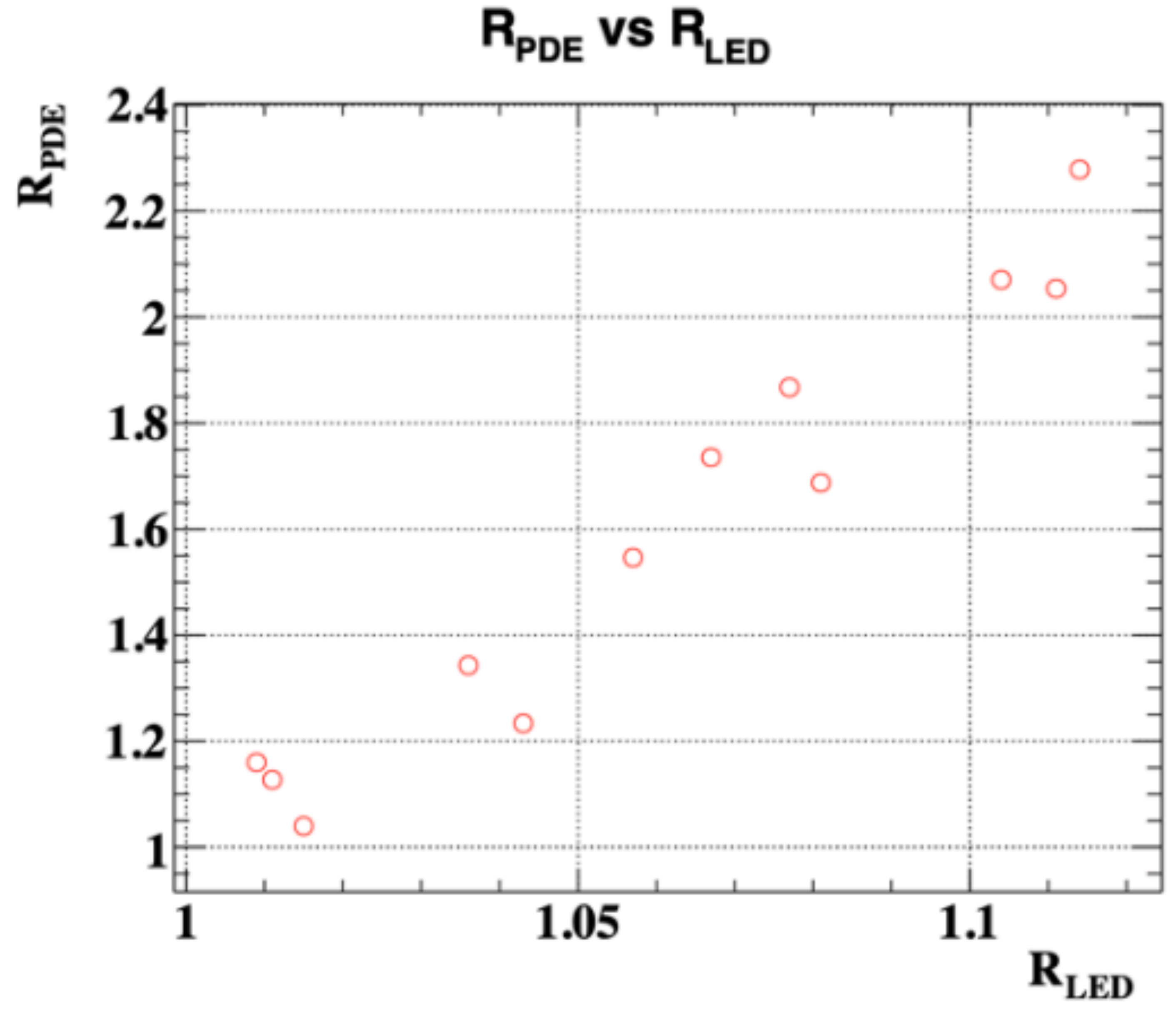
- Stable operation was not possible due to Corona discharge in 2019
  - Adding small amount of CO2, O2, H2O, Alcohol etc. is suggested by the previous studies
- Different gas mixtures were tested in 2020 under muon beam
  - Gas mixture: pure He/IsoButane 90:10
  - Additives tested: CO2, Water, O2, Isopropanol
  - It seems adequate gas mixture for stable operation was finally found
    - He/iB 88.2%:9.8%+H2O 3500ppm+pure O2 2%
    - Nominal HV at MEG II intensity (7×107μ/s) successfully.
- One broken wire is suspected
  - Due to corrosion by water?
  - Water must be changed with something else
  - Isopropyl alcohol at 1% added, and it worked!
  - O2 concentration reduced down to 0.5%
    - Attachment of electrons loses electron in the drift
    - Impact on the gas gain
    - Better to reduce the O2 concentration

Annealing effect measured by VUV light



- PDE is measured by α sources after the detector is filled with liquid xenon
- PDE recovery after annealing is confirmed
  - PDE value up to ~20% for several MPPCs (full recovery by annealing)
  - Consistent with PDE measured in lab.
- PDE_{VUV} (α) vs PDE_{VIS} (LED)
  - Clear correlation is observed
    - $PDE_{VIS} \sim 0.1 \times PDE_{VUV}$
  - We can monitor PDE recovery by blue LED during annealing

LED charge recovery



Possible Cause

- **Surface damage by VUV-light**

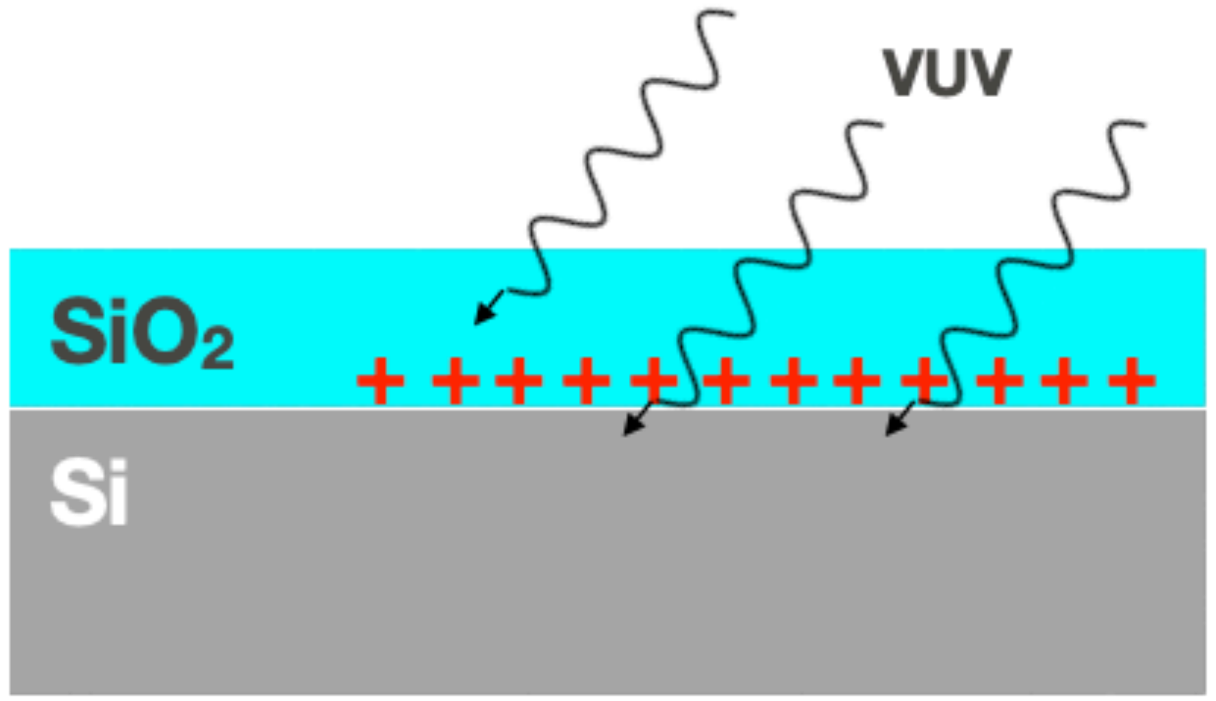
  Electron-hole pair generated in SiO_2 by VUV light

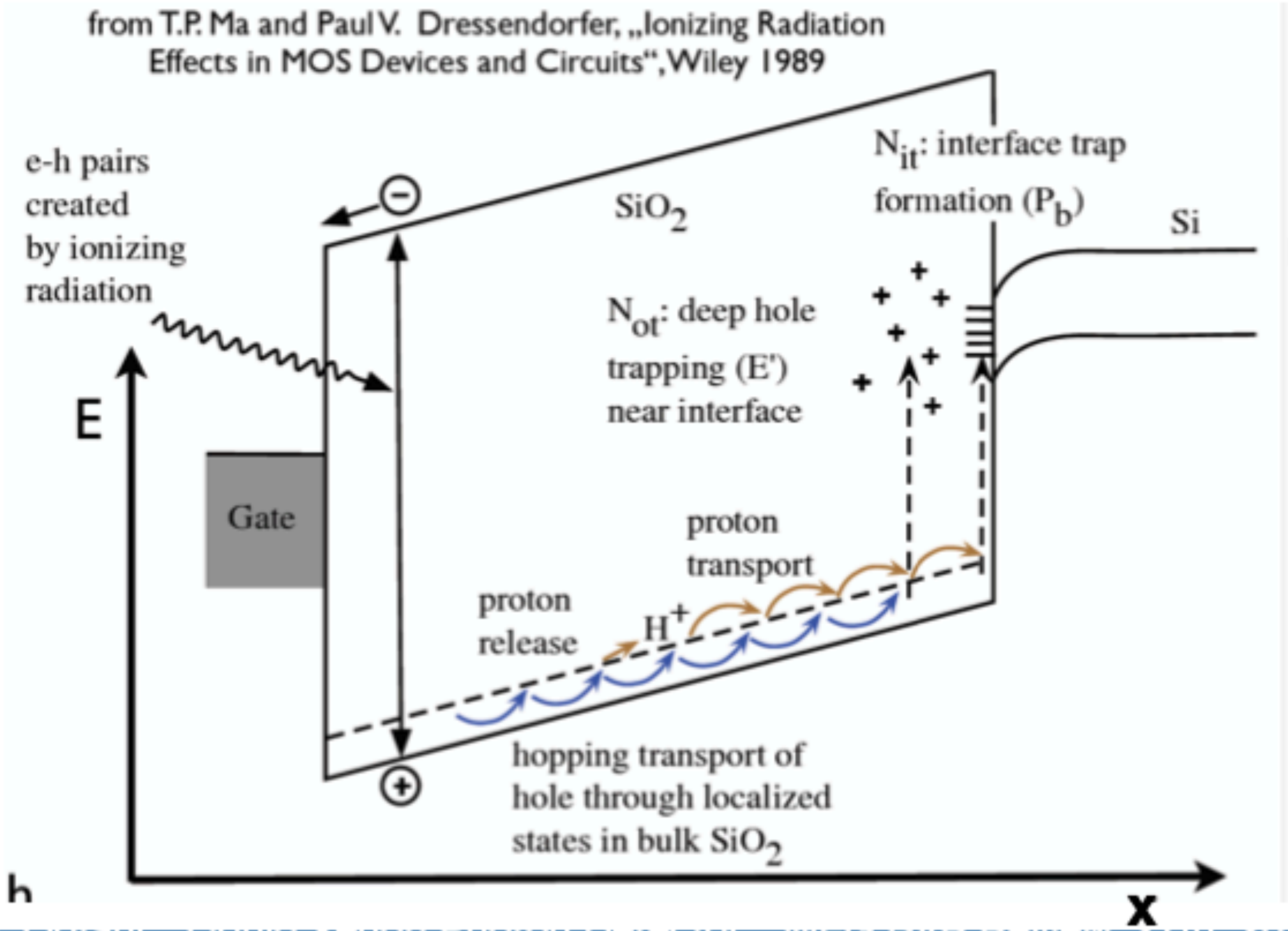
  →Holes are trapped at interface SiO_2 - Si

  →Accumulated positive charge will reduce electric field near Si surface, reducing collection efficiency of charge carrier

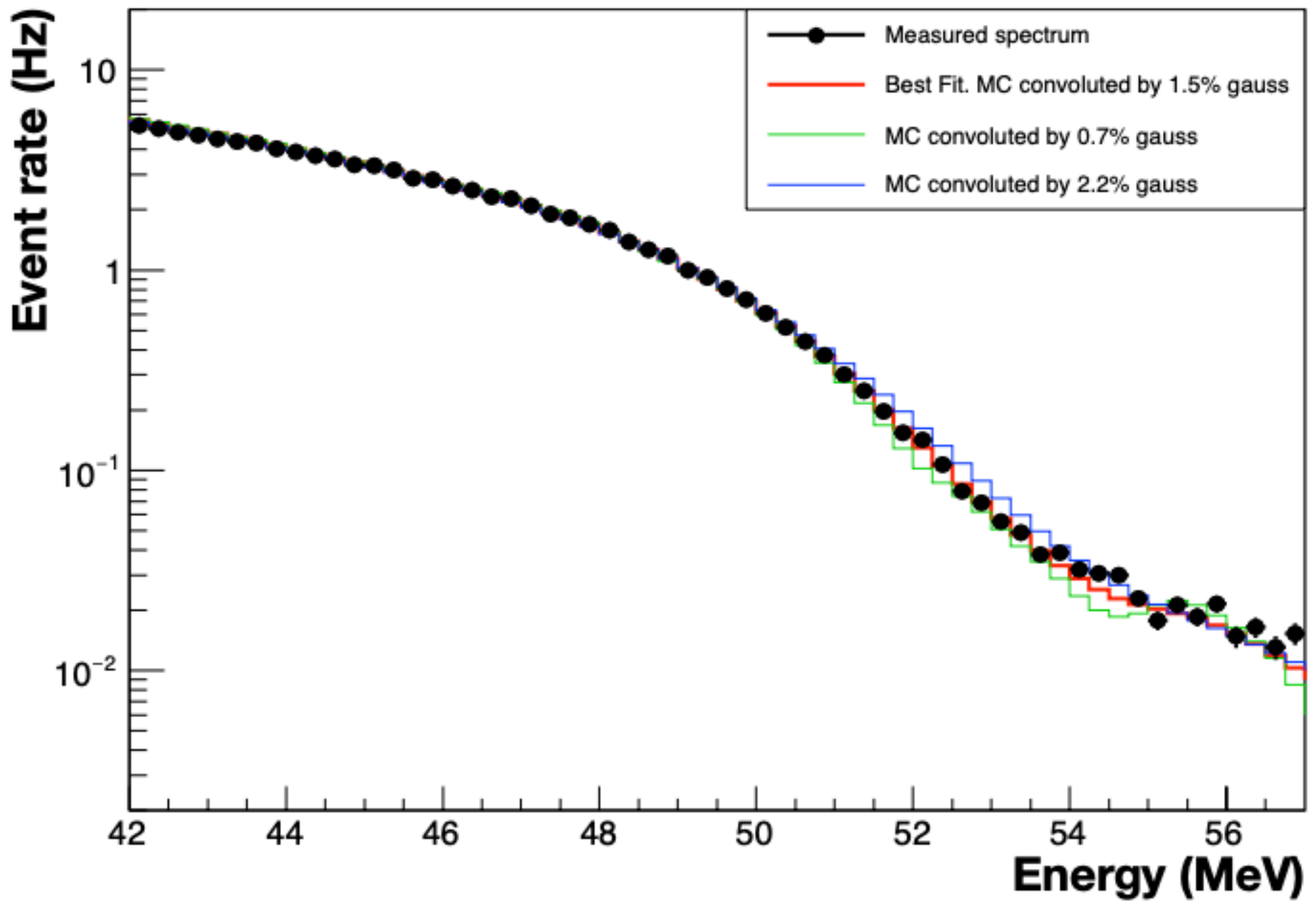
    - N.B. charge carrier generated within 5nm at Si surface for VUV

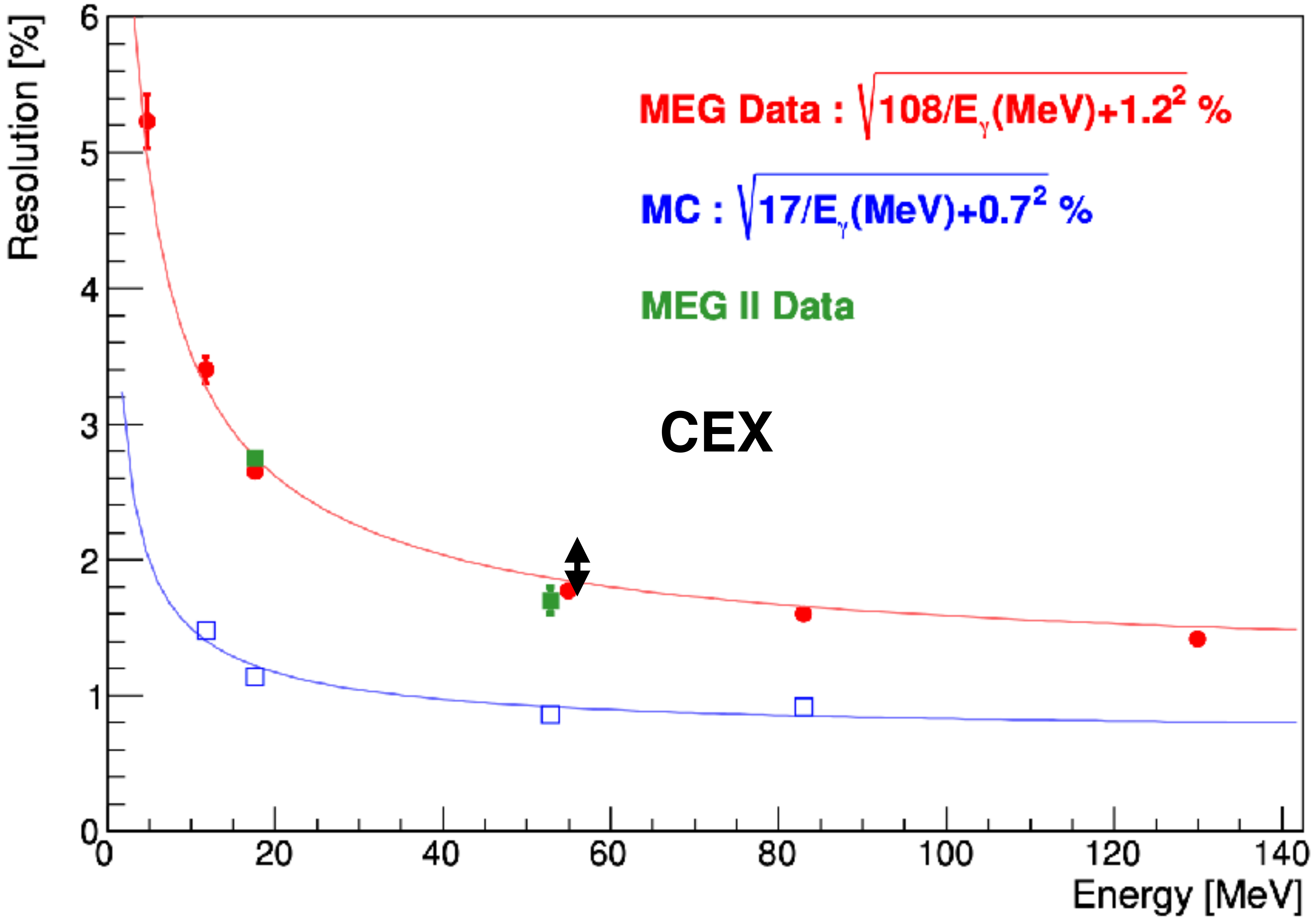
- **Similar phenomena are known for UV photo diode**
  - Degradation happens only with much larger amount of light at room temp.
  - Degradation seems accelerated at low temp.



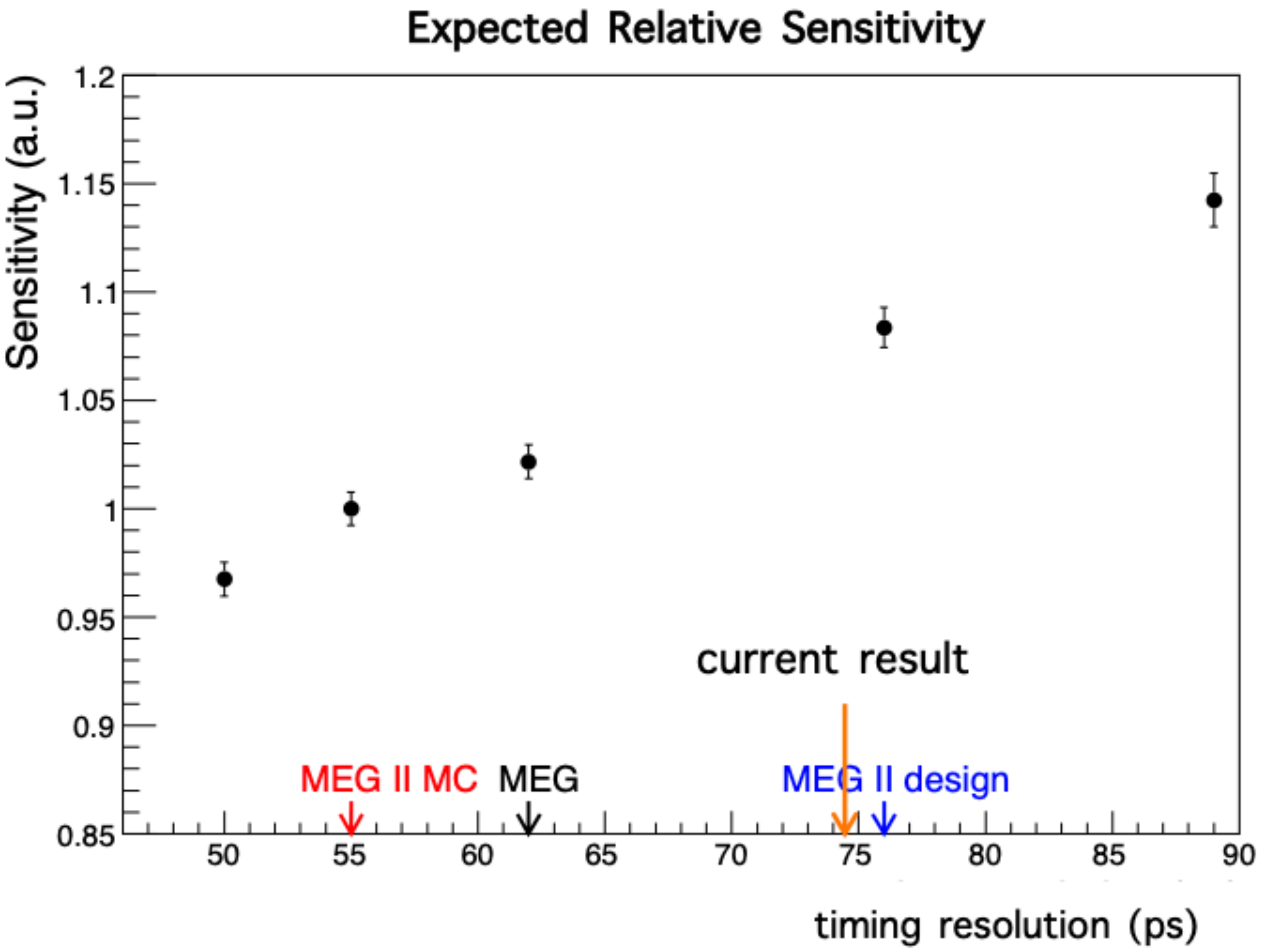


LXe energy resolution





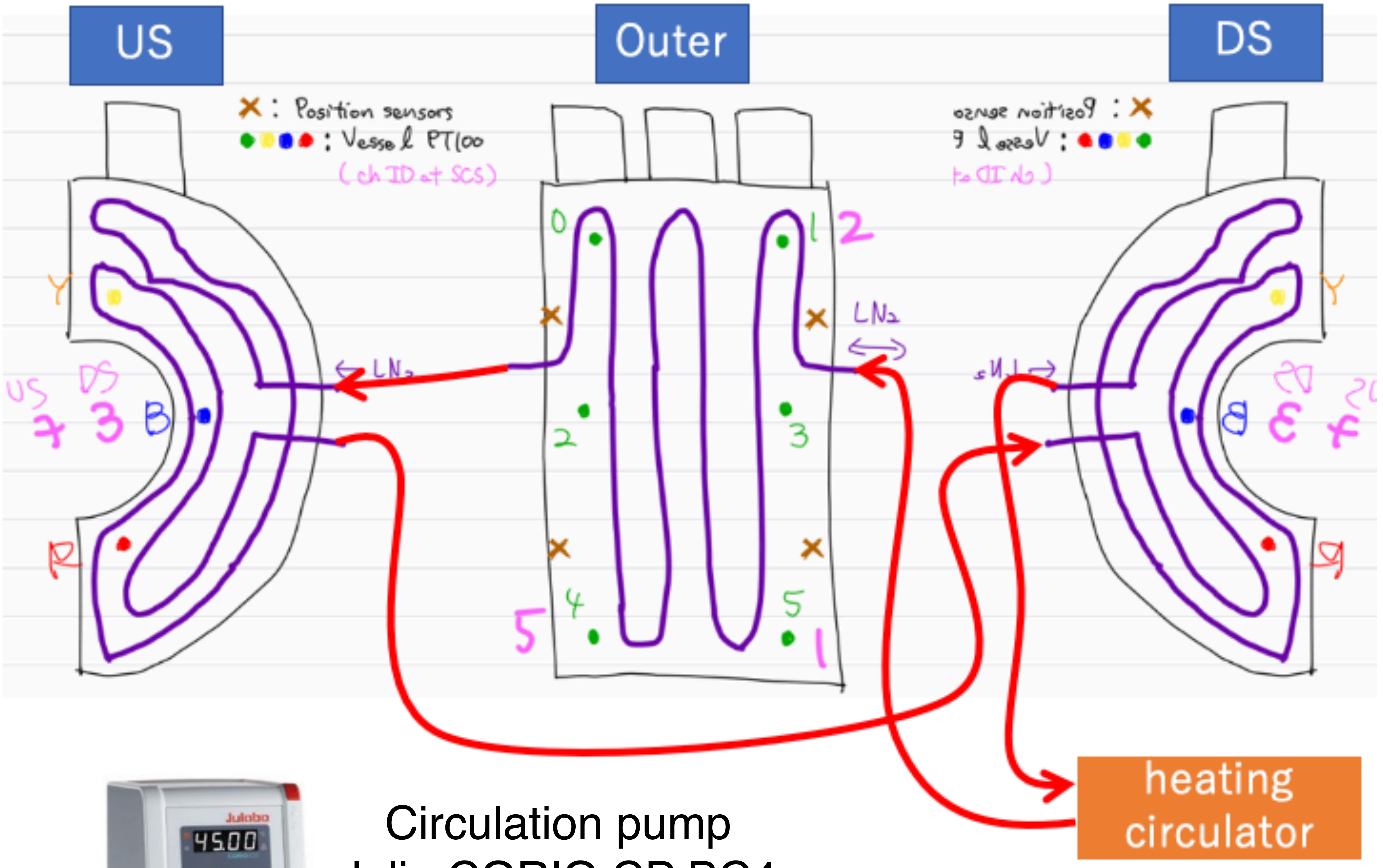
LXe time resolution



- The current absolute time resolution would deteriorate the sensitivity by 7%

Towards annealing for all MPPCs

- Two methods are currently considered
- Hot water circulation in LN_2 pipe
  - Heater(+pump) used for the hot water circulation
    - to heat the detector to 40°C, 4 hours at minimum
  - All channels can be annealed at once
  - No need for cabling : easy
  - Temperature can be measured at PMT holders
  - Remaining issues
    - How fast can we warm the detector?
    - Annealing is successful at 40°C?
    - Can we drain water from LN_2 pipe completely?
- Joule heat with HV module
  - The basic principle for annealing is confirmed
  - Cabling work is required
  - Temperature increase must be carefully checked to anneal more channels at the same time
- Hot water method is better, but basic tests for both will be done this year, and annealing for all MPPCs will be done in 2022.

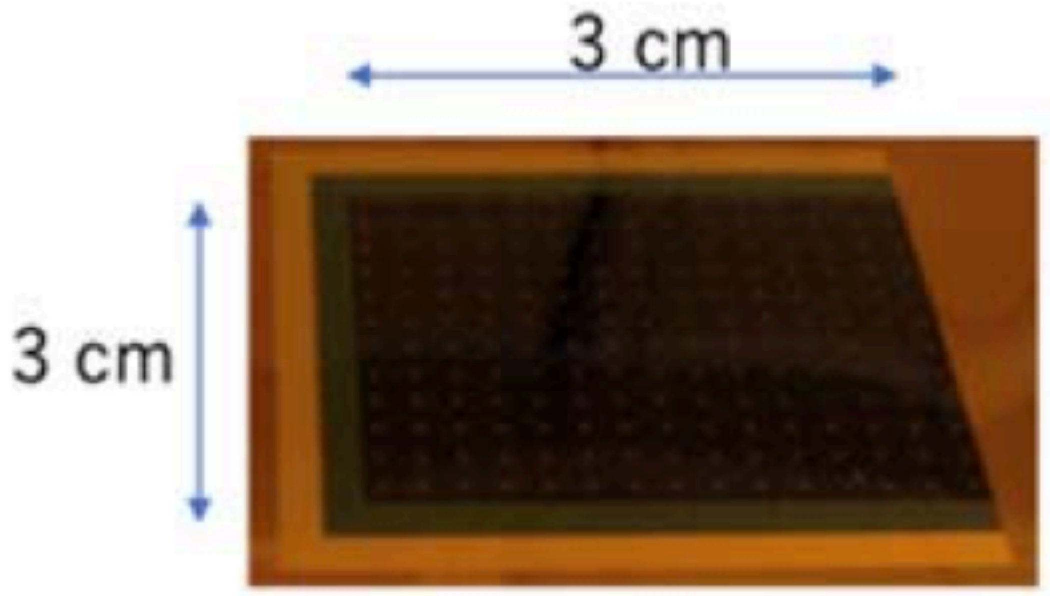


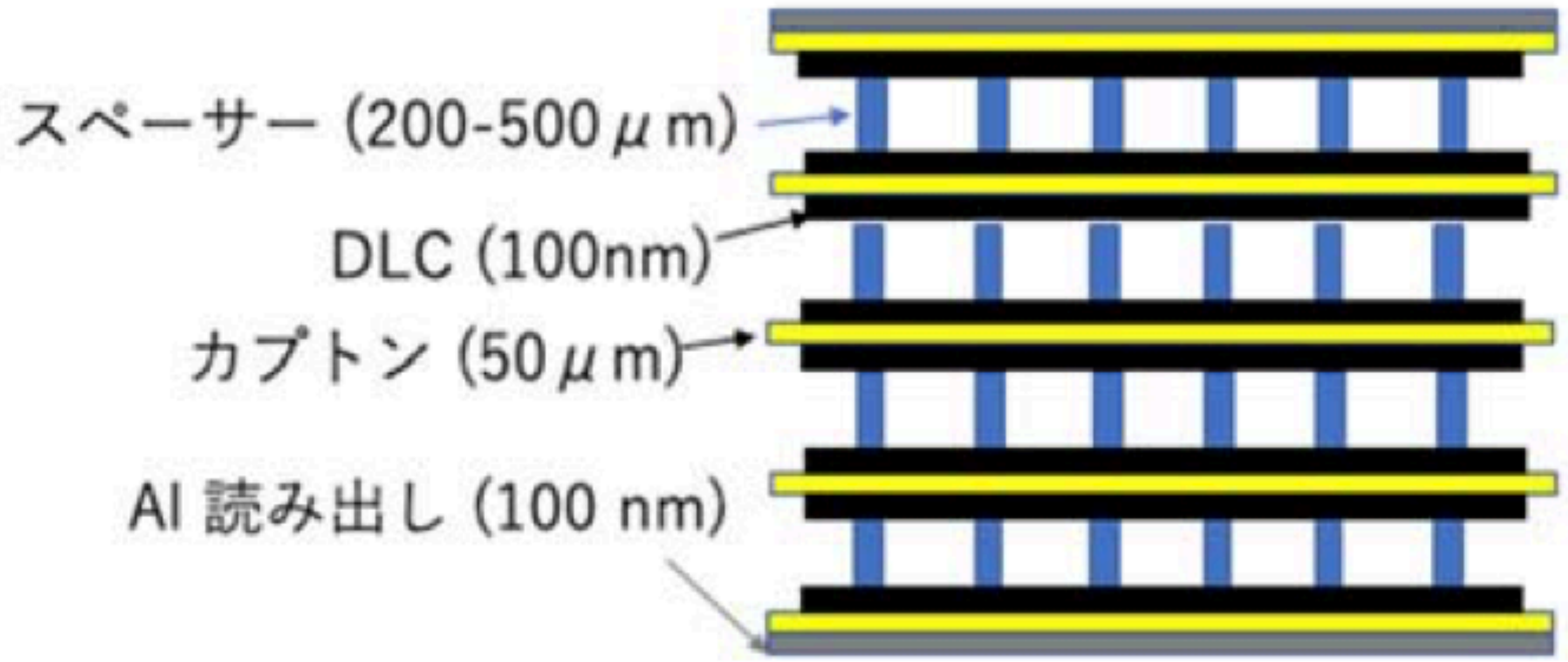
Circulation pump
Julio CORIO CP BC4

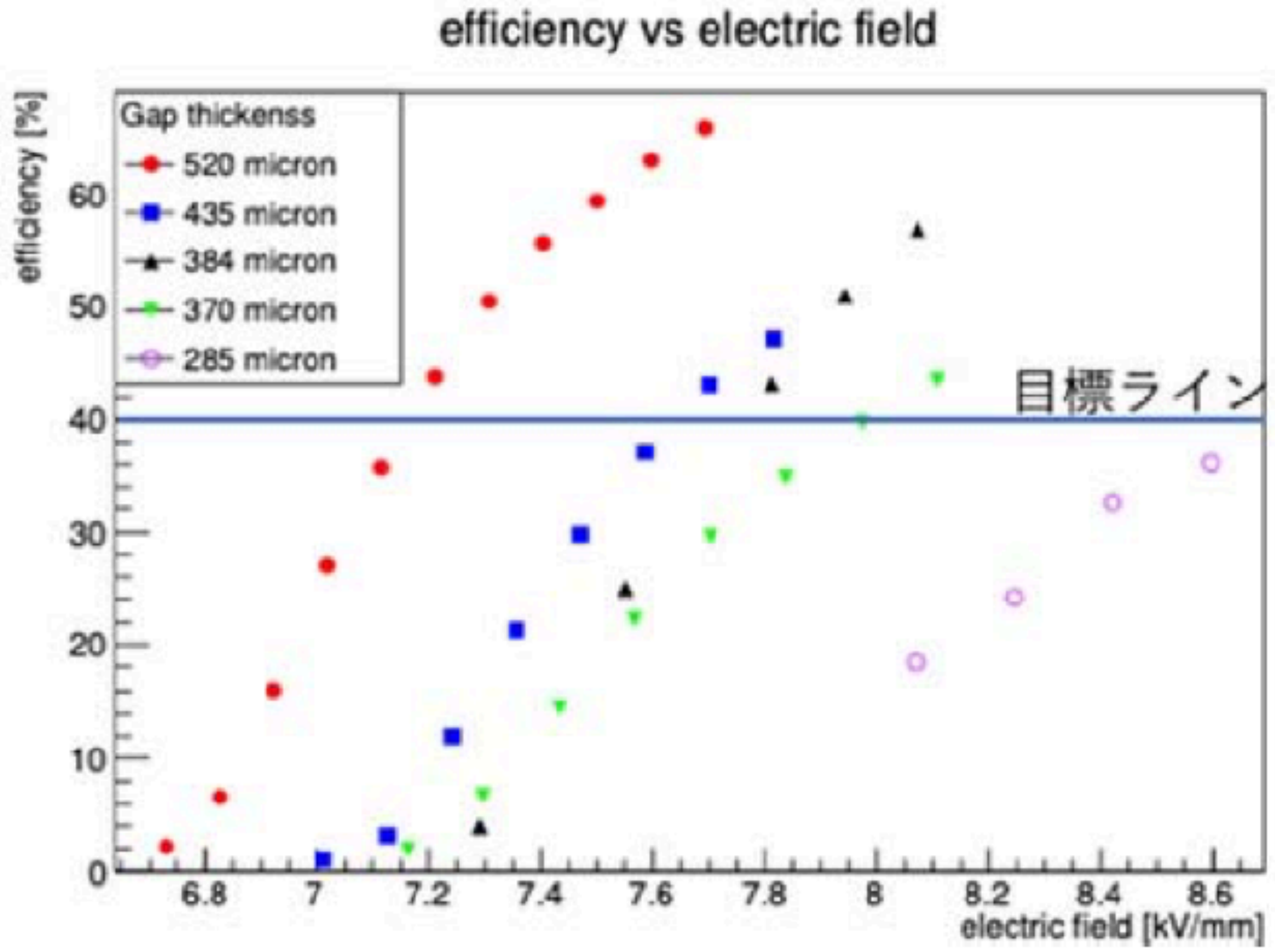
Test HV module
(30ch, high current)

US RDC (RPC)

- US RDC
  - High intensity muon beam will pass through
  - High detection efficiency (90% for 1-5 MeV e^+)
  - Ultra low material budget (<0.1% X_0)
  - High rate tolerant (10^8 μ/s)
  - Diameter 20cm
- Ultra thin gaseous detector (RPC) with diamond-Like-Carbon (DLC) resistive electrode
  - R134a (Freon) based gas
  - Gap thickness : 200μm - 2mm
  - DLC: high resistive material w/ mixed structure of sp^2 bond and sp^3 bond
  - DLC sputtering on 50 μm Kapton
  - Resistivity adjustable
  - High efficiency can be achieved by multilayer design







Future μ→eγ

- Positron spectrometer
  - HV-MAPS + scintillator or mRPC
  - Resolutions
    - energy 0.3%(150keV)・time 30ps・angle 6mrad・detection efficiency 70%
- Gamma converter + pair spectrometer
  - Resolutions
    - energy 0.4% (200keV)・time 30ps・position 0.2mm・angle 50mrad・detection eff. 60%